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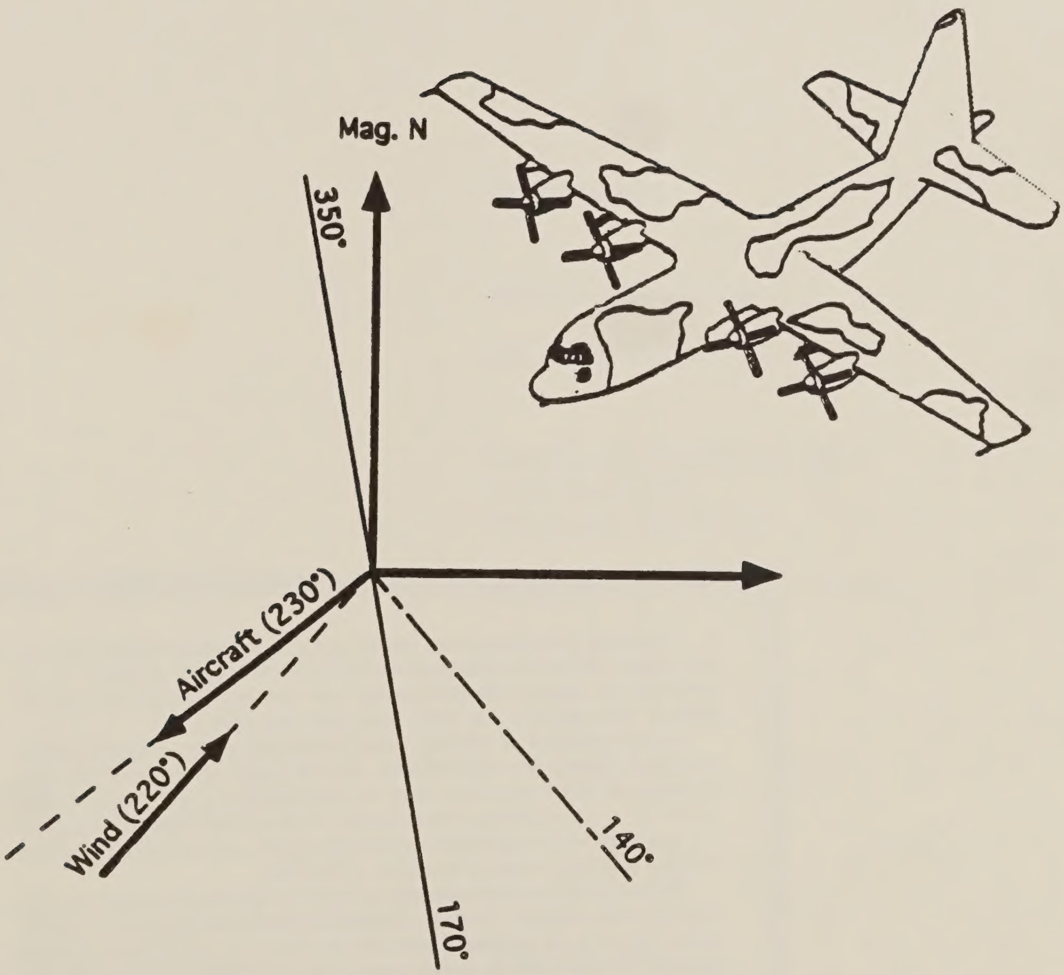
FSCBG Model Comparisons With The C-130 Spray Trials



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Pesticides used improperly can be injurious to human beings, animals, and plants. Follow the directions and heed all precautions on labels. Store pesticides in original containers under lock and key—out of the reach of children and animals—and away from food and feed.

Apply pesticides so that they do not endanger humans, livestock, crops, beneficial insects, fish, and wildlife. Do not apply pesticides where there is danger of drift when honey bees or other pollinating insects are visiting plants, or in ways that may contaminate water or leave illegal residues.

Avoid prolonged inhalation of pesticide sprays or dusts; wear protective clothing and equipment, if specified on the label.

If your hands become contaminated with a pesticide, do not eat or drink until you have washed. In case a pesticide is swallowed or gets in the eyes, follow the first aid treatment given on the label, and get prompt medical attention. If a pesticide is spilled on your skin or clothing, remove clothing immediately and wash skin thoroughly.

NOTE: Some States have restrictions on the use of certain pesticides. Check your State and local regulations. Also, because registrations of pesticides are under constant review by the U.S Environmental Protection Agency, consult your local forest pathologist, county agriculture agent, or State extension specialist to be sure the intended use is still registered.

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FSCBG MODEL COMPARISONS WITH THE C-130 SPRAY TRIALS

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Summary

This paper describes FSCBG simulations for the aerial application of several formulations of Bacillus thuringiensis from a C-130 aircraft. Twenty-five trials with four different insecticide formulations were performed in February 1990 at a New Mexico State University test site northeast of Las Cruces, NM. Deposition variables generated during analysis of the field test data are compared to FSCBG simulations of ground deposition for each of the twenty five trials. The field study was designed to evaluate operational spray performance and was not designed for FSCBG validation. Nevertheless, the study provides an opportunity to evaluate aspects of FSCBG, and despite some difficulty interpreting the test data, peak correlation of FSCBG predictions to the field data is R^2=0.80 for drops and R^2=0.50 for mass. A scatter plot of predicted and field data volume median diameter shows good correlation. Further field testing is recommended in order to better model the effect of aerosol impaction on raised collector surfaces.

1. Introduction

This paper is the first of four validation studies to be accomplished in 1993-1994 for the Forest Service Cramer-Barry-Grim (FSCBG) aerial spray model (Teske et al. 1993) and its near-wake Agricultural Dispersal (AGDISP) model (Bilanin et al. 1989). Field tests of several different aerial spray pesticides have been performed with a variety of aircraft. Ground deposition data from each of these tests is available for comparison with FSCBG and AGDISP simulations. This paper is concerned with a test performed in February 1990 to characterize a C-130 spray system for applying Bacillus thuringiensis for the control of gypsy moth.

The USDA Forest Service in cooperation with the United States Army has developed FSCBG incorporating AGDISP as its near-wake model. FSCBG predicts the transport and behavior of pesticide sprays released from aircraft, influenced by the aircraft wake and local atmospheric conditions, through downwind drift and deposition to total accountancy and environmental fate. The AGDISP near-wake representation solves a Lagrangian system of equations for the position and position variance of material released from each nozzle on the aircraft. The FSCBG far-wake representation begins with the results of AGDISP at the top of a canopy or near the ground, and solves a Gaussian diffusion equation to recover ground deposition. FSCBG includes an analytic dispersion model for multiple line sources oriented in any direction to the wind, an evaporation model for volatile spray components, a canopy penetration model for forest canopy interception, and an accountancy model to recover environmental fate of released material.

Drop size distributions give the mass distribution of material as it is atomized by each nozzle. Drops containing volatile material (such as water) begin to evaporate immediately upon entering the atmosphere, with the local temperature, relative humidity and relative wind speed determining the evaporation rate. The presence of the aircraft wake (with its vortical structure) may move material to unanticipated locations. Ambient winds superimpose additional horizontal velocity vectors on the spray material. Canopy deposition removes spray material from the air and prevents nonvolatile components from reaching the ground. Every aspect of the spray process is affected by the size and significance of atmospheric and aircraft-generated turbulence.

Meteorological calculations generate the background wind speed, temperature and relative humidity profiles. Evaporation calculations track the time rate of decrease of drop size. Canopy calculations remove additional material through impaction on vegetation. Near-wake calculations follow the behavior of released spray near the aircraft, and when out of wake influence or at the top of the canopy, hand off to the dispersion calculations to predict the dosage, concentration and deposition at user-designated downwind locations.

Technical aspects of the FSCBG model are discussed in Teske et al. (1993). Comparisons with data include downslope drift in open terrain (Barry et al. 1993), a drift study over desert (Boyle et al. 1975), canopy penetration in Southern pine (Rafferty et al. 1982), open terrain and canopy penetration in Douglas-fir (Teske et al. 1991), eastern oak (Anderson et al. 1992), and Gambel oak (Rafferty and Grim 1992).

The C-130 E model spray system test referred to in this paper took place from February 22 to February 27, 1990 at the Jornada Test Site near Las Cruces, New Mexico. United States Air Force 907 TAG operations and maintenance personnel performed

twenty five trials in cooperation with the USDA Forest Service and New Mexico State University. The purpose of these trials was to evaluate the operational capability of the U.S. Air Force Modular Aerial Spray System (MASS) for aerial application of Bacillus thuringiensis var. kurstaki (Bt) for gypsy moth control. Two major objectives were to characterize the system using neat (undiluted) formulations of Bt in the low-volume mode and to collect meteorology data to be used in FSCBG and AGDISP validation studies.

Ground deposition data and meteorology data from these trials were summarized and analyzed by Huddleston et al. (1990). After each spray pass, an image analysis system was used to evaluate droplet deposition over a line perpendicular to or parallel with the wind (for into-wind or crosswind trials, respectively). Deposition variables such as drops per square centimeter and volume median diameter (VMD) were then generated from the field data for each trial. Meteorological data was recorded and summarized in detail in PSL-90/32 (Physical Science Lab 1990). Specific meteorological data required for FSCBG evaluation studies was further summarized during field data analysis and is included in the results presented in Huddleston et al. (1990).

2. Field Trials Summary

2.1 Spray Site

The New Mexico State University Jornada Test Site, located 40km northwest of Las Cruces, is at an elevation of 1312m. The site is relatively flat rangeland with a mean canopy height of 36cm. A diagram of the test circle is shown in Figure 1. Twelve lines 305m long radiate every 30 degrees from the center. Sampling stations occurred every 7.6m and consisted of a 10.2 by 12.7cm card secured to a hardboard plate and attached to the top of a wooden stake at the mean canopy height.

2.2 Meteorology Collection

Two towers, one 49m to the northeast of the test circle center and one 518m to the southwest of the center, monitored winds, temperature, solar radiation and relative humidity on the test site. The towers were provided by the White Sands Atmospheric Sciences Laboratory. Data was collected at 2, 8, 16 and 30m using the Transportable Atmospheric Characterization System (TACS) as described in PSL-90/32.

Mean wind direction and speed for each height were calculated from the one-minute averages for 10 minutes after the spray pass. Relative humidity and air temperature were recorded at 2m, and temperature difference was recorded for 8, 16 and 30m.

Before each spray trial, wind direction readings from the towers, smoke drift from a candle placed at the center of the test circle, and the aircraft doppler radar readings were used to determine the desired aircraft heading. The aircraft then passed once over the edge of the test circle for another estimate of wind speed and direction before performing the spray run.

Relative humidity at the test site was generally highest early in the morning. All spray trials were conducted between 0631 and 1133 hours, except for the shakedown trial (trial 1). Nevertheless, no relative humidity readings higher than 63% were recorded during the first five days of spray trials. High relative humidity readings (70 to 99%) were recorded on the last day of testing, February 27, when the oil-based Bt formulation Dipel 8L was sprayed. Meteorological conditions for each trial are summarized in Table 1. The temperature and wind speed data shown are averages of the four readings at 2, 8, 16 and 30m. Wind direction shown is the average of the four readings, defined with respect to Magnetic North.

2.3 Spray Aircraft Configuration

The spray trials were conducted with a Lockheed Hercules C-130E aircraft equipped with MASS in a low-volume mode configuration. The aircraft was equipped with long wing booms and had a span of 41.75m (Biery 1990). The MASS low-volume mode configuration consisted of 6.1m spray booms mounted under each wing. Twenty nozzles were in use on each wing, located every 15cm along the boom from 70 to 85 percent of the semispan. 8030 and 8050 Flat Fan Tip nozzles were used in TeeJet housings oriented straight down (90 degrees). Table 2 shows the nozzle tips used for each trial and the flow rates of the spray material.

2.4 Spray Characteristics

Aircraft altitude for the trials varied from 30.5 to 61m AGL and ground speed was 103mps. Tables 2 and 3 from Huddleston et al. (1990) summarize the spray system and aircraft system variables for each trial.

For trials designated into-wind, the aircraft flew over the center of the test circle. For trials designated crosswind the aircraft flew either over the center or upwind of the center. Trials 1 through 22 and trial 24 were single swaths. Trial 23 consisted of three crosswind swaths starting at the center and subsequently at 183 meter intervals upwind. For trial 25, two crosswind swaths were flown at 183m apart. All trials were calibrated for a 183m swath width except trials 1 and 2 (274m swath width) and trial 7 (213m swath width).

Dipel 8AF, Dipel 8L, Foray 48B and SAN 415 formulations of Bt were sprayed undiluted at application rates recommended for gypsy moth control (272 l/min to 863 l/min). Dipel 8AF, Foray 48B and SAN415 are aqueous solutions and Dipel 8L is an oil-based solution. The drop size characteristics for each formulation are given in Table 4. Rhodamine WT and oil red dyes were added at 0.5% to give contrast for analysis of the drop stains.

Kromekote cards were placed on all of the sampling stakes just before the spray pass. For each trial, an optimum card line was identified which was composed of cards from the two opposite lines that were either perpendicular to or parallel with the wind (for crosswind and into-wind trials, respectively). All cards were collected approximately 15 minutes after the spray pass. Cards from the optimum line were analyzed shortly afterward to determine stain size and density with the Swath Kit image analysis system. Optimum card line data from each trial is presented and analyzed in Huddleston et al. (1990). This data is the basis for comparison with FSCBG predictions of deposition.

2.5 Results

Although the low-volume MASS mode used throughout the test was not designed for spraying aerial pesticide, field test data results indicate that each Bt formulation was adequately atomized (Huddleston et al. 1990). The trials were not designed to compare formulations of Bt. In general, into-wind trials showed an uneven, narrower swath deposition pattern while crosswind trials showed better deposition and a wider swath width.

Some problems inherent to the data were identified during analysis (Huddleston et al. 1990 and Biery 1990). Most trials occurred in low relative humidity, a condition that would tend to retard deposition and reduce droplet size and the degree of droplet spread, thus reducing deposition and the collection efficiency of the cards. Trials with the Dipel 8L oil-based formulation were conducted in very high relative humidity, so that little or no evaporation was likely to occur. Application flow rate was difficult to stabilize because of short spray times (10-22 seconds) and the spray was intermittent or late during trials 5, 6, and 12. Visual observation at the test site indicated that the drops were unusually large during some of the trials and that the spray, at times, came down in flakes (R. Sanderson, New Mexico State University, private communication; specific formulations referred to are unknown).

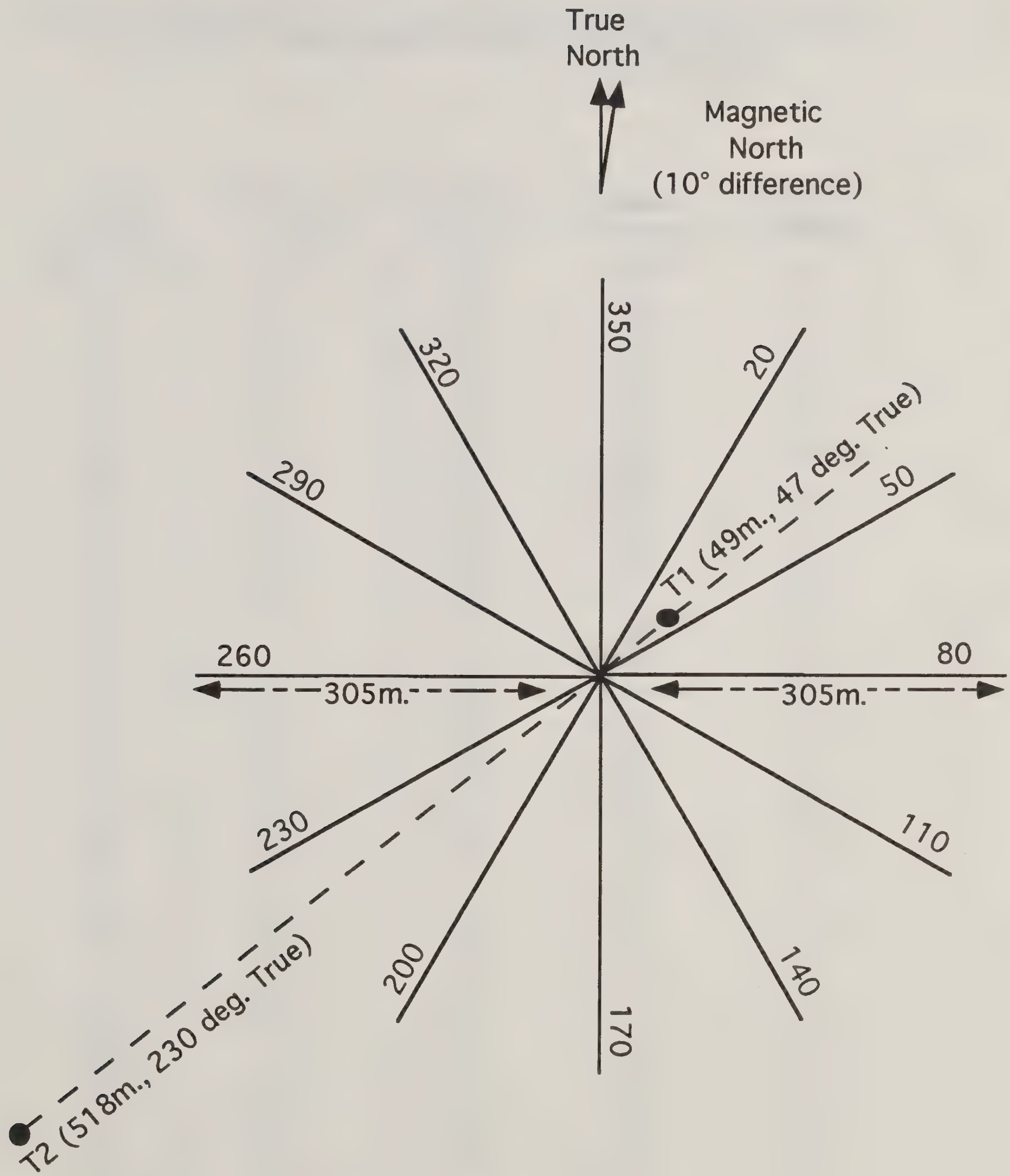

Figure 1. Card line orientation and TACS tower location at the Jornada Test Site. T1 and T2 designate TACS towers. Note that there is a 10 degree discrepancy between True North and Magnetic North. TACS data (wind direction) was recorded relative to True North while card alignment and airplane heading was recorded relative to Magnetic North.

TABLE 1: Summary of meteorology data for the C-130 spray trials. Average wind direction shown here has been adjusted to correspond to Magnetic North.

Trial #	Average Temperature (deg C)	Relative Humidity (%)	Average Wind Speed (m/s)	Wind Direction (deg Mag N)
1	12.9	22	1.85	344
2	-4.9	63	1.75	360
3	0.8	40	0.50	19
4	4.6	31	1.18	220
5	-2.9	63	0.65	20
6	0.2	43	2.10	262
7	3.4	37	2.00	301
8	5.0	36	2.40	328
9	7.7	32	1.90	312
10	10.7	27	1.25	316
11	-3.1	53	1.65	350
12	-2.4	50	1.65	356
13	0.8	37	1.05	13
14	7.0	24	1.05	245
15	10.0	22	0.50	285
16	13.2	18	0.55	189
17	4.0	40	0.80	255
18	6.2	30	1.35	294
19	8.0	99	2.42	324
20	7.6	98	2.28	340
21	12.9	99	0.35	200
22	12.8	98	1.42	340
23	14.4	98	0.88	56
24	15.7	98	0.62	188
25	15.9	72	1.55	151

TABLE 2: Spray system variables for the C-130 spray trials.

Trial #	Formulation	Nozzle	Flow Rate (l/min)
1	Foray 48B	8050	NA
2	Foray 48B	8050	863
3	Foray 48B	8050	545
4	Foray 48B	8050	413
5	Foray 48B	8050	435
6	Foray 48B	8050	363
7	Foray 48B	8050	568
8	Foray 48B	8050	409
9	Foray 48B	8050	469
10	Foray 48B	8050	602
11	Dipel 8AF	8030	386
12	Dipel 8AF	8030	352
13	Dipel 8AF	8030	272
14	Dipel 8AF	8030	401
15	Dipel 8AF	8030	484
16	Dipel 8AF	8030	511
17	SAN 415	8030	579
18	SAN 415	8030	647
19	Dipel 8L	8030	394
20	Dipel 8L	8030	553
21	Dipel 8L	8030	322
22	Dipel 8L	8030	454
23	Dipel 8L	8030	401*
24	Dipel 8L	8030	314
25	Dipel 8L	8030	469**

* Average for the three runs conducted
** Average for the two runs conducted

TABLE 3: Aircraft variables for the C-130 spray trials.

Trial #	Aircraft Weight (kg)	Aircraft Height (m)	Orientation to Wind
1	NA	38.1	into
2	54431	38.1	into
3	53524	38.1	into
4	52163	61.0	into
5	54431	61.0	into
6	52617	61.0	into
7	51256	38.1	cross
8	49895	38.1	cross
9	48988	38.1	cross
10	47627	38.1	cross
11	53977	38.1	into
12	53070	38.1	into
13	51710	38.1	cross
14	53070	38.1	cross
15	52163	38.1	cross
16	51256	30.5	cross
17	54885	38.1	into
18	53977	30.5	cross
19	55987	38.1	into
20	53860	38.1	into
21	55375	30.5	into
22	54128	30.5	into
23	52721	38.1	cross
24	51349	38.1	cross
25	48988	38.1	cross

TABLE 4: Drop size characteristics for the four formulations of Bt used in the C-130 spray trials (John W. Barry, USDA Forest Service, private communication, and Skyler and Barry 1990). Note that Foray 48B, Dipel 8AF and SAN 415 are aqueous solutions and Dipel 8L is an oil-based solution.

Formulation	Specific Gravity/ Density	Volatile Fraction
Foray 48B	1.16	0.15
Dipel 8AF	1.195	0.15

Average Diameter (micrometers)	Mass Fraction
45.88	0.1807
73.78	0.3105
106.35	0.2724
138.62	0.1486
171.03	0.0614
203.42	0.0167
235.88	0.0060
268.32	0.0021
301.32	0.0013
334.77	0.0003

Formulation: SAN 415

Specific Gravity = 1.12
Volatile Fraction = 0.15

Average Diameter (micrometers)	Mass Fraction
45.88	0.0512
73.78	0.0997
106.35	0.2194
138.62	0.2829
171.03	0.1875
203.42	0.0970
235.88	0.0443
268.32	0.0132
301.32	0.0043
334.77	0.0004
366.72	0.0001

Formulation: Dipel 8L

Specific Gravity = 0.90
Volatile Fraction = 0.10

Average Diameter (micrometers)	Mass Fraction
45.88	0.0562
73.78	0.1307
106.35	0.2945
138.62	0.3402
171.03	0.1453
203.42	0.0284
235.88	0.0035
268.32	0.0009
301.32	0.0003

3. FSCBG Simulation of Field Test Data

The objective of this paper is to compare FSCBG predictions of deposition with the field test results. A detailed description of input parameters necessary for FSCBG modeling may be found in Teske and Curbishley (1991).

Spray application rate, aircraft altitude and aircraft weight, relative humidity and temperature vary for each trial according to the field test data as previously shown in Tables 2 and 3.

Aircraft configuration and powerplant data required by FSCBG is summarized in Table 5. FSCBG version 4.1 includes a C-130 module in its library of standard aircraft configurations. This data was adjusted for the wing span specified in the field test data (41.75m).

Huddleston et al. (1990) show compass roses for each trial with aircraft flight path, mean wind direction, and card line analyzed (optimum card line). Mean wind direction was defined to be the mean of the mean directions at each of the four heights, adjusted to Magnetic North. New compass roses were generated to account for the difference in orientation between FSCBG and the field test data. FSCBG requires wind direction to be input in degrees from the aircraft flight path. Figure 2 shows one such compass rose calculation for trial #4. Mean wind speed data is available at 2, 8, 16 and 30m. Mean wind velocity to be used in FSCBG predictions was curve fit through this data.

Drop size characteristics for each Bt formulation vary as shown previously in Table 4. This data is part of the FSCBG version 4.1 standard drop size library and was suggested by J. Barry, USDA Forest Service (private communication). During preliminary simulations of test data the number of drops deposited per square centimeter was consistently much higher than test data results, by two or three orders of magnitude depending on the Bt formulation being examined. To address this discrepancy, drop size data was corrected to account for the collection efficiency expected when drops of the sizes specified impact on an elevated flat plate.

May and Clifford (1967) have defined the collection efficiency of aerosol particles dropping onto objects of various shapes. Assuming that the collection efficiency of a disc is close to that of a rectangular card, Figure 3 shows the relation of aerosol impaction efficiency, E, to the dimensionless impaction parameter, P. P is defined as $P=\rho V d^2/18\mu l$ where ρ is the specific gravity of the droplet, V is its velocity, d is its diameter, μ is the air viscosity and l is the length of the collector (in this case, the average length).

To calculate the impaction parameter P it is necessary to determine the droplet velocity V at the point of impaction. McDonald (1960) has defined the impact velocity (or terminal velocity) Vt of a droplet as a function of its diameter, as shown in Figure 4. There is also a horizontal velocity component Vh due to the wind speed measured during each trial. Since the wind speed for each trial was determined for various heights and the cards are nearly at ground level, the horizontal velocity at impaction is assumed to be half of the mean wind speed at 10m defined for each trial. Total velocity at impaction is then the square root of Vt^2 plus Vh^2.

The effect of collection efficiency was tested extensively before arriving at the present assumption. This assumption is a compromise that best fits all twenty-five spray trials.

Aerosol impaction efficiency was calculated for each drop size in each trial and the drop size distributions for each trial were modified accordingly. Table 6 shows this process for trial 4. The new drop size distributions were then used to generate the FSCBG predictions.

TABLE 5: C-130 Aircraft characteristics.

Aircraft Type	Lockheed Hercules C-130
Wing span	41.75 m
Planform area	170.94 m sq
Drag coefficient	0.1
Propeller radius	2.06 m
Propeller efficiency	0.8
Blade RPM	1020.0
Flying speed	103.0 mps

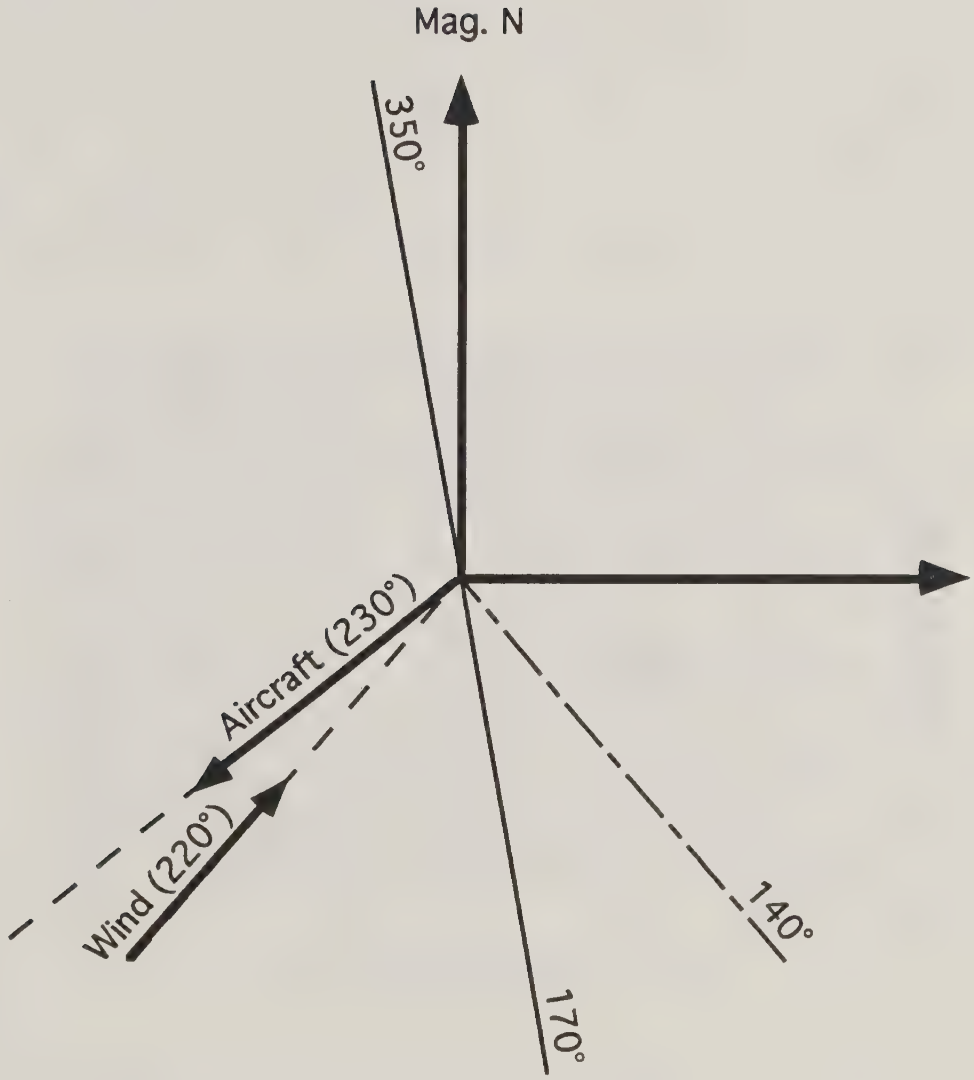

Figure 2. Compass rose for C-130 spray test trial 4, all angles given with respect to Magnetic North:

Aircraft heading = 230 degrees
Average wind direction = 220 degrees

Optimum card line used for field test data 350/170

FSCBG predicts ground deposition variables along a line perpendicular to aircraft flight path (140 degrees).

FSCBG requires wind direction relative to aircraft heading (in this case, 350 degrees).

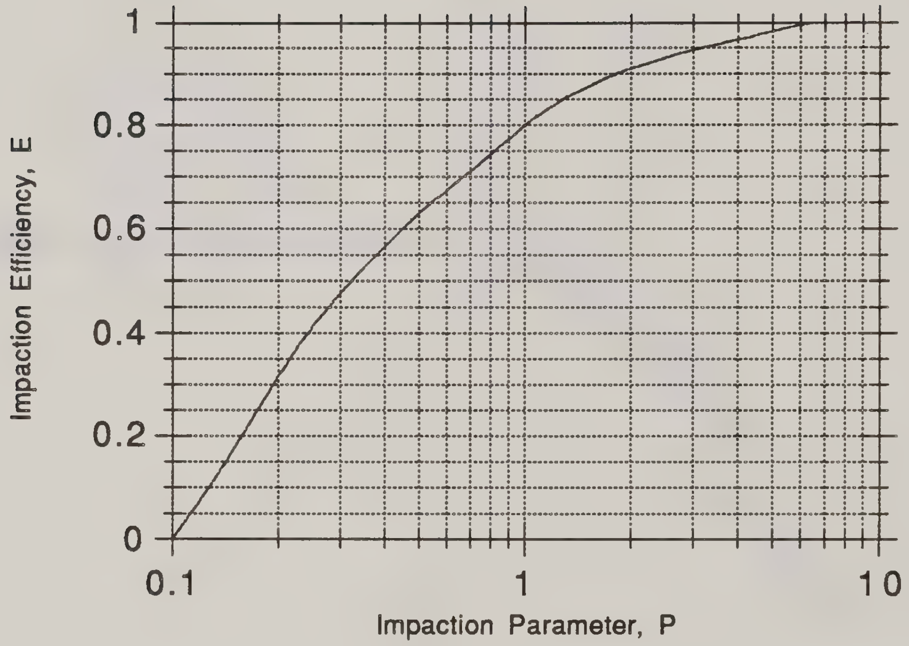

Figure 3. Impaction efficiency of discs, as shown in May and Clifford (1967).

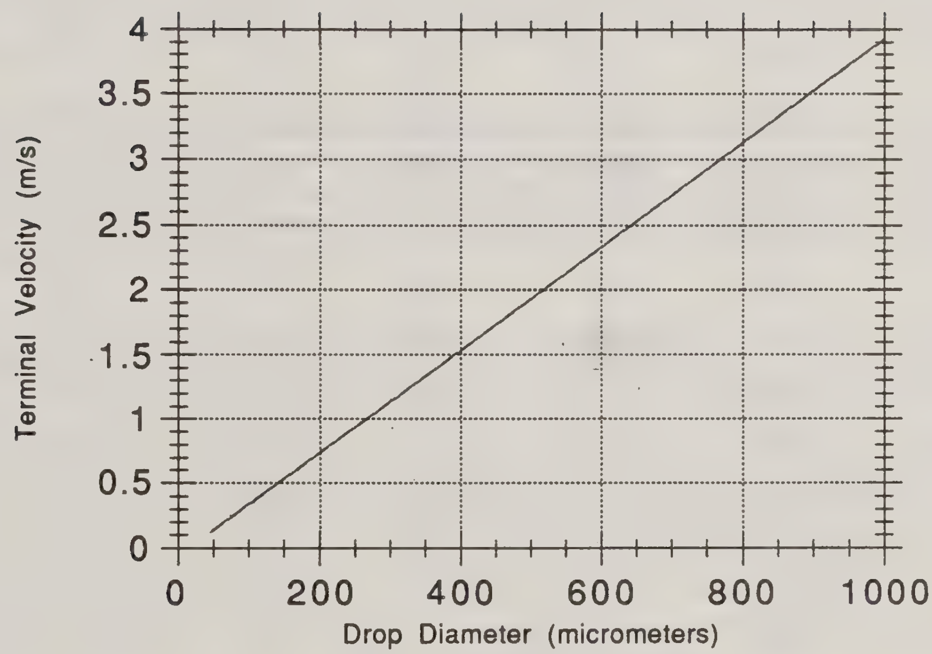

Figure 4. Terminal velocity for droplets of specific diameter.

TABLE 6: Effect of impaction efficiency correction on drop size distribution for trial #4. Mean wind speed at 10m =1.201 m/s.

Average Drop Size (micrometers) d	Mass Fraction	Terminal Velocity (m/s) *Vt*	Total Velocity (m/s) V	Impaction Parameter P	Impaction Efficiency E	New Mass Fraction
45.88	0.1807	0.20	0.63	0.04	0.00	0.0000
73.78	0.3105	0.25	0.65	0.11	0.04	0.0115
106.35	0.2724	0.35	0.69	0.23	0.32	0.0878
138.62	0.1486	0.50	0.78	0.46	0.57	0.0848
171.03	0.0614	0.60	0.85	0.77	0.70	0.0432
203.42	0.0167	0.75	0.96	1.23	0.80	0.0133
235.88	0.0060	0.80	1.00	1.72	0.86	0.0052
268.32	0.0021	0.95	1.12	2.51	0.90	0.0019
301.32	0.0013	1.15	1.30	3.65	0.94	0.0012
334.77	0.0003	1.35	1.48	5.13	0.98	0.0003
TOTAL	1.0000					0.2492

4. Results and Discussion

Comparison plots of field test deposition data and FSCBG deposition predictions for each of the twenty five spray trials are presented in the Appendix. Deposition variables examined are drops per square centimeter over the optimum card line and volume in Infectious Units (IU) per square centimeter over the optimum card line. FSCBG predicts the volume deposited in nanoliters (nl) per square centimeter. Table 7, obtained from R. Sanderson (private communication), shows the BIU (billion IU) per gallon for each of the Bt formulations used.

FSCBG simulations are plotted as solid lines and field test data is plotted as open circles. Each set of comparison plots is briefly evaluated below. FSCBG predictions were adjusted to account for several factors: orientation of the field test deposition data; numbering of data cards along the optimum card line; and position of the airplane over the test circle.

FSCBG generates deposition data along a line perpendicular to the aircraft flight path; this is not always the same line as the optimum card line from the field test data. For example, Figure 2 shows that for trial 4, the optimum card line and the FSCBG prediction line differ by 30 degrees. When necessary, FSCBG predictions are adjusted to the orientation of the optimum card line.

FSCBG also defines distance along the line of predicted deposition differently than the measured distance from field test data. Card line distance from the field test was supposed to be measured from the outer edge of the test circle inwards, starting at the pilot's extreme left. FSCBG defines the distance from the position of the aircraft centerline, positive to the pilot's right. All plots showing predicted data over distance use the field test convention, with distance measured from the edge of the test circle. It should be noted that this convention was not always observed during field test data analysis. Data from trials 1, 3, 5, 10, 11 and 25 appear to have been reversed. When FSCBG predictions for these trials are adjusted accordingly, they correlate well with the test data. Furthermore, data from trials 1, 6, 7, and 9 appear to have been taken from the center of the test circle instead of from the outer edge.

All into-wind trials were conducted with the aircraft flying over the center of the test circle. For many of the crosswind trials, the aircraft passed over a specific point in the circle as defined in the test summary in Huddleston et al. (1990). FSCBG simulations are adjusted to account for the position of the aircraft with respect to the test circle center. However, it should be noted that aircraft position in the crosswind trials was not defined using the stated field test convention as card numbers were defined from the test circle center outwards.

Two of the trials, numbers 20 and 22, were conducted with flaps at 30 degrees. FSCBG predictions of the amount of drops deposited for these two trials are quite good.

Trials 23 and 25 consisted of multiple passes of the aircraft over the test circle. FSCBG predictions have been adjusted to account for the extra material deposited. An average flow rate was used to predict the deposition for the first pass, and the same deposition (at an increment of 183m swath width upwind) was assumed for subsequent passes.

Table 8 compares the integrated mass deposition for the C-130 spray trials with the integrated mass deposition predicted by FSCBG, and the initial mass released from the aircraft (adjusted for volatility). The results indicate that collection efficiency is an important consideration for elevated collection cards, and that some of the trials collected an extraordinary amount of material while some collected much less than would be expected. For trials 21 and 22, where the integrated field data deposition is greater than the nonvolatile mass released from the aircraft, recovery on the cards is suspect. Trials 8, 9, 17 and 18 show very small amounts of material collected. Trial 25, a multiple-swath trial, shows much less material collected than would be expected under conditions of high relative humidity and light wind. Conversely, integrated field data deposition for trials 19 and 24 shows that over 90% of the nonvolatile mass released made it to the collection cards despite a moderate wind in trial 19 and variable wind in trial 24. Based on these observations, trials 8, 9, 17, 18, 19, 21, 22, 24 and 25 were not included in calculations for correlation coefficient R^2 for mass and drops.

Field test data and FSCBG simulations are also compared by means of Table 9, which shows the volume median diameter (VMD) of droplets for each trial. Since VMD gives an overall representation to the deposition, all trials are included here, even those with obvious collection problems (as discussed above). Figure 5 shows a scatterplot of the simulated and field test values of VMD. All trials except trial 19 (which shows an improbably high field test value of VMD) are included on the scatterplot. A least square line through the results gives a slope of 0.87.

Table 10 contains the correlation coefficients comparing the field test data (drops and mass) with FSCBG predictions. This table gives a quick summary of the test results and corresponding FSCBG predictions. As previously noted, correlation coefficients for trials 8, 9, 17, 18, 19, 21, 22, 24 and 25 are not included in the calculation. Correlation for trial 16 is also excluded because of machine error and unstable conditions during this trial, as noted in Huddelston et al. (1990). The average correlation for the remaining trials is R^2= 0.47 for drops, with values ranging from R^2=0.18 to R^2=0.80. The corresponding average for mass is R^2=0.30, with values ranging from R^2= 0.07 to R^2=0.50. The average correlation for VMD is R^2=0.47. These consistently low correlation coefficients are a disappointment, and suggest difficulty with data collection and interpretation, and collection efficiency effects.

The same consistent techniques discussed previously were applied to each of the 25 spray trials. A summary of results follows, with figures found in the Appendix.

TRIAL 1:

Trials 1-10 use the Foray 48B formulation of Bt. This was a shakedown run at low relative humidity (25%). No pesticide flow rate or aircraft weight were recorded, so representative values of these variables were assumed for the simulation. Nevertheless, the FSCBG prediction is quite good.

TRIAL 2:

The VMD prediction matches the field data, and the deposition patterns match quite well. Relative humidity was 63%, higher than most of the other aqueous formulation trials.

TRIAL 3:

Although the level of deposition correlates well, FSCBG predicts two clear peaks and field data shows a different shape. Volume level correlates very well, but the VMD shown in the field test analysis appears to be too high. The predicted deposition is also shifted along the card line. Data analysis of this trial by Huddleston et al. (1990) indicated high evaporation.

TRIAL 4:

FSCBG simulation of trial 4 shows good correlation with field test data despite low relative humidity conditions.

TRIAL 5:

FSCBG predicts lower levels of deposition than actually occurred. Field test data indicates that the spray came on late during this trial (Huddleston et al. 1990) and that the wind was very light. This may account for the abrupt single peak in field data deposition apparent near the aircraft centerline. Despite the disparity in both comparison plots, the VMD correlates fairly well.

TRIAL 6:

The peak in drops is predicted very well. Field notes indicate that the spray came on late during this trial and was very short in duration, possibly accounting for the difference in spread of the predicted deposition and the field test data.

TRIAL 7:

FSCBG accurately predicts the level and shape of the deposition as well as the VMD despite a slight shift along the card line. Note that conditions during this trial and trial 6 were very similar.

TRIAL 8:

Predicted values of deposition are twice as high as the field test data. Table 8 indicates that only a small amount of the mass released from the aircraft was recovered on the elevated cards.

TRIAL 9:

Predictions show the same shape but higher levels of deposition than the field test data. Again, the amount of mass recovered on the elevated cards was very small.

TRIAL 10:

Both plots show good correlation despite very low relative humidity conditions. VMD does not correlate well. The amount of mass recovered was smaller than predicted.

TRIALS 11,13 and 14:

These trials were run with the Dipel 8AF formulation of Bt. All of them show a slight under-prediction of deposition, although the VMDs correlate well. Relative humidity for trial 11 was over 50%, but for trials 13 and 14 it was much lower. The shape of the deposition for these three runs is correct, and the volume plots also correlate well. Trials 11 and 13 show very good correlation to drops in Table 10, but trial 14 does not correctly predict the peak value in drops and so does not show good correlation to drops or to mass.

TRIALS 12 and 16:

Although the level of deposition predicted is correct, both these predictions do not show enough spread along the card line. Field notes for trial 12 indicate intermittent atmospheric flow. Trial 16 was conducted in the lowest relative humidity conditions of the whole test (18%). Huddleston et al. (1990) note that the peak in deposition at 510m is probably machine error and that the trial was conducted in unstable conditions.

TRIAL 15:

FSCBG underpredicts the amount and the spread of drop deposition.

TRIALS 17 and 18:

These trials use the SAN 415 formulation of Bt. Trial 17 is an into-wind run and trial 18 is a crosswind run. Predictions for both trials are at considerable variance with the data. Trial 17 was conducted in a very light wind, yet field test data shows a large amount of deposition at the edge of the test circle; field notes indicate that the entire swath was not captured. FSCBG predicts a narrow deposition pattern over the test circle center, which would be expected in a light wind.

The field notes for trial 18 caution that a significant wind shift occurred just after application and may have affected the recovery.

Table 8 shows that the amount of mass recovered in both of these trials was less than 10% of the mass released from the aircraft.

TRIAL 19:

Trial 19 is the first trial of the Dipel 8L oil-based Bt formulation. Relative humidity during all the Dipel 8L trials except trial 25 was above 98%, so very little evaporation occurred. Nevertheless, the amount of mass recovered in this trial was surprisingly large. Although specified in the field test data as an into-wind run, this trial actually occurred in a partial crosswind. Despite a moderate wind, FSCBG favorably

predicts the level of deposition. Note that the VMD calculated from the field data is abnormally high.

TRIALS 20 and 22:

These trials were conducted with flaps at 30 degrees. Trial 20 shows very good correlation to data. Trial 22 does not show adequate spread of the deposition, but VMD correlation is good. Note that the amount of mass recovered in trial 22 is greater than the nonvolatile mass released from the aircraft.

TRIAL 21:

FSCBG severely underpredicts the deposition for this trial, and from the shape of the field data, it may be concluded that FSCBG would be unable to expand the spread of the predicted deposition to match the data. Once again, the amount of mass recovered exceeds the nonvolatile mass released from the aircraft, suggesting that the field data shown is suspect.

TRIAL 24:

Field notes indicate that the deposition peak from 0 to 100m should be considered with caution. FSCBG does not predict the other deposition peak at 550m and does not adequately predict the spread of the field data. However, field notes also indicate that winds were variable. The amount of mass recovered in this trial is very large.

TRIALS 23 and 25:

These were multiple swath trials. Trial 23 consisted of three runs, the first over the test circle center and each subsequent one at 183m intervals upwind. Trial 25 consisted of two such swaths. FSCBG predicts the average level of deposition for trial 23 fairly well; however, the correlation to mass and drops (as shown in Table 10) is not very good. Trial 25 does not correlate quite as well. It should be noted that field data for this trial appear to have been taken from the test circle center instead of from the edge. Also, this trial was run in a much lower relative humidity than trial 23 (72%). Field notes indicate that the wind speed changed between the two passes. Furthermore, the amount of mass recovered seems very small for a multiple-swath trial.

TABLE 7: Infectious Units (IU) per gallon of Bt formulation.

Bt Formulation	BIU/gal
Foray 48B	48.0
Dipel 8AF	64.0
SAN 415	41.5
Dipel 8L	64.0

TABLE 8: Integrated mass comparison for the C-130 spray trials.

Trial #	Nonvolatile Mass Released (l/m)	Integrated Field Data Deposition (l/m)	Integrated FSCBG Deposition (l/m)	FSCBG Mass Fraction Predicted
1	NA	0.0401	0.0421	0.3562
2	0.1191	0.0744	0.0436	0.3620
3	0.0752	0.0369	0.0129	0.1696
4	0.0570	0.0185	0.0142	0.2492
5	0.0600	0.0350	0.0092	0.1534
6	0.0501	0.0185	0.0174	0.3702
7	0.0784	0.0253	0.0291	0.3792
8	0.0564	0.0088	0.0231	0.4165
9	0.0647	0.0075	0.0225	0.3552
10	0.0831	0.0126	0.0215	0.2651
11	0.0533	0.0326	0.0175	0.3092
12	0.0486	0.0208	0.0168	0.3485
13	0.0375	0.0115	0.0088	0.2342
14	0.0553	0.0204	0.0129	0.2342
15	0.0670	0.0309	0.0120	0.1727
16	0.0705	0.0374	0.0124	0.1763
17	0.0799	0.0078	0.0347	0.4358
18	0.0893	0.0036	0.0476	0.5341
19	0.0575	0.0516	0.0325	0.5632
20	0.0807	0.0616	0.0456	0.5658
21	0.0470	0.0505	0.0139	0.2921
22	0.0663	0.0696	0.0310	0.4682
23	0.1755*	0.0660	0.0643	0.3720
24	0.0458	0.0418	0.0150	0.3272
25	0.1370*	0.0210	0.0638	0.4789

* multiple-swath trials: based on average flow rate

TABLE 9: Volume Median Diameter (VMD) calculations for each trial.

Trial #	VMD (Field Test Data)	VMD (FSCBG)
1	215	116
2	114	114
3	215	130
4	140	118
5	130	144
6	149	121
7	128	119
8	133	114
9	144	117
10	156	116
11	126	113
12	97	104
13	134	118
14	118	120
15	117	143
16	116	136
17	108	147
18	117	124
19	421	113
20	75	116
21	65	140
22	114	116
23	181*	140
24	95	139
25	183*	113

* calculated for only one swath

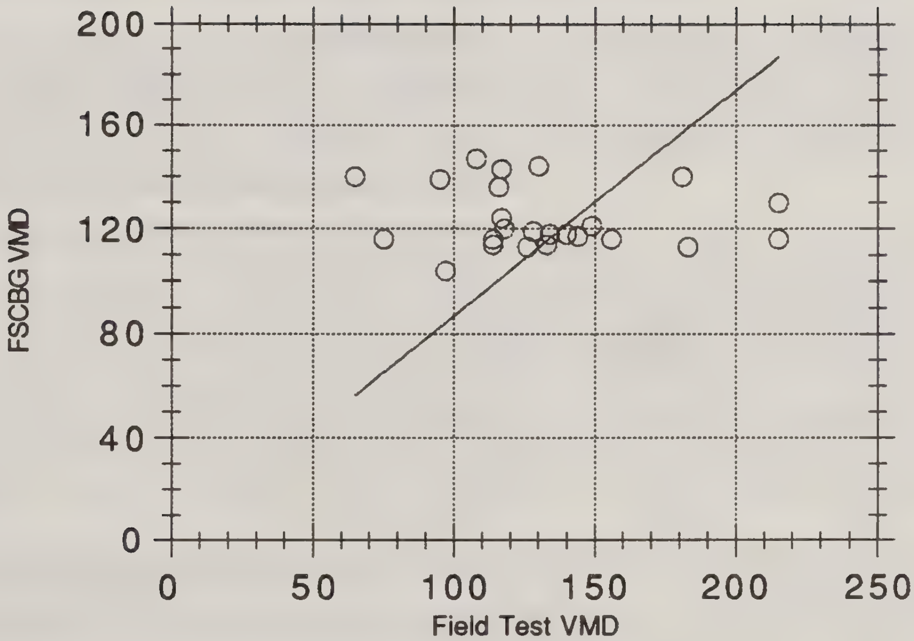

Figure 5. Simulated and field test values of Volume Median Diameter (VMD). Slope = 0.87.

TABLE 10: Correlation coefficients for trials 1-25 comparing field data and FSCBG predictions for drops and mass deposited.

Trial #	Correlation to Drops	Correlation to Mass	Comments
1	0.56	0.31	Shakedown run; flow rate assumed
2	0.45	0.49	Good comparison
3	0.35	0.40	Prediction shows right level but wrong shape
4	0.59	0.29	Good comparison
5	0.38	0.15	Under predicted
6	0.70	0.26	Peak value in drops predicted well
7	0.28	0.44	Good comparison
8			Very small amount of mass collected
9			Very small amount of mass collected
10	0.52	0.37	Good comparison
11	0.71	0.32	Good comparison
12	0.20	0.14	Intermittent flow
13	0.80	0.50	Good comparison
14	0.18	0.27	Good comparison
15	0.28	0.16	Under predicted
16			Trial conducted in unstable conditions
17			Deposition profile wrong; small amount collected
18			Very small amount of mass collected
19			Good comparison
20	0.77	0.26	30 degrees flaps; good comparison
21			Mass collected exceeds mass released
22			30 degree flaps; mass collected exceeds mass released
23	0.22	0.07	Multiple-swath trial (3 swaths)
24			Variable wind
25			Multiple-swath trial (2 swaths)
Average	0.47	0.30	

5. Conclusions

It must be noted that the field data presented some difficulties and the FSCBG predictions shown in the appendix are the best compromise over all the trials. Several assumptions were made to generate the FSCBG model for these trials, each of which has a significant impact on the final predictions shown. Drop size distributions for the Bt formulations were assumed to be those in Table 4, but gave such improbable deposition patterns that they were modified using a collection efficiency correction technique. This correction was itself a compromise and should be further studied. Some aspects of the field experiment were hard to interpret, notably the distance measurements throughout the test and the orientation of card data and meteorological data. Clearly, some of the data points (particularly on the volume plots) appear extraneous.

Nevertheless, making a consistent set of assumptions to model the trials with FSCBG, the predicted deposition for drops correlates reasonably well with the field test data. The overall R^2=0.47 (drops), while lower than we would like, seems acceptable for this operational field test. Trials 6, 11, 13 and 20 showed correlation above 0.70, and trials 1, 4, and 10 showed correlation above 0.50.

Predicted deposition for mass is not as good. The overall R^2=0.30 (mass) indicates the difficulties encountered in interpreting the field test data as well as the importance of the assumptions made regarding drop size distribution, drop spreading on cards and collection efficiency of the sampling stations. Some problems are readily apparent. There are several trials (1, 6, 9, 10, 12, 16) in which the level of deposition and its general shape are predicted very well, but the spread of drops along the card line is not correct. All of these trials except 16 had a significant crosswind, and 9, 10 and 16 were performed in very low relative humidities (32%, 27% and 18%, respectively).

Conversely, there are several trials which adequately predict the spread or the shape of the deposition but not the level. Trials 15, 16, 21, and 24, all of which have very little crosswind, indicate poor correlation with field data. Predicted deposition is high for trials 2, 8, and 9, each of which has a relatively large crosswind. The crosswind is directly related to the horizontal component of the droplet velocity, which is in turn related to the impaction parameter, P, and to the impaction efficiency E. For all of these trials, a trial-specific correction for collection efficiency would probably result in better prediction of deposition, but we felt that a consistent approach should be used if we are to generalize the implementation of collection efficiency on elevated cards in FSCBG.

Some type of correction for collection efficiency is clearly needed, although the present technique needs to be refined to be more inclusive. With the correction as presented, trials with small crosswind velocities as well as some of the trials with large crosswind velocities show poor correlation with test data. A carefully prescribed field test is suggested to further examine the effect of aerosol impaction efficiency on raised collectors.

6. Acknowledgement

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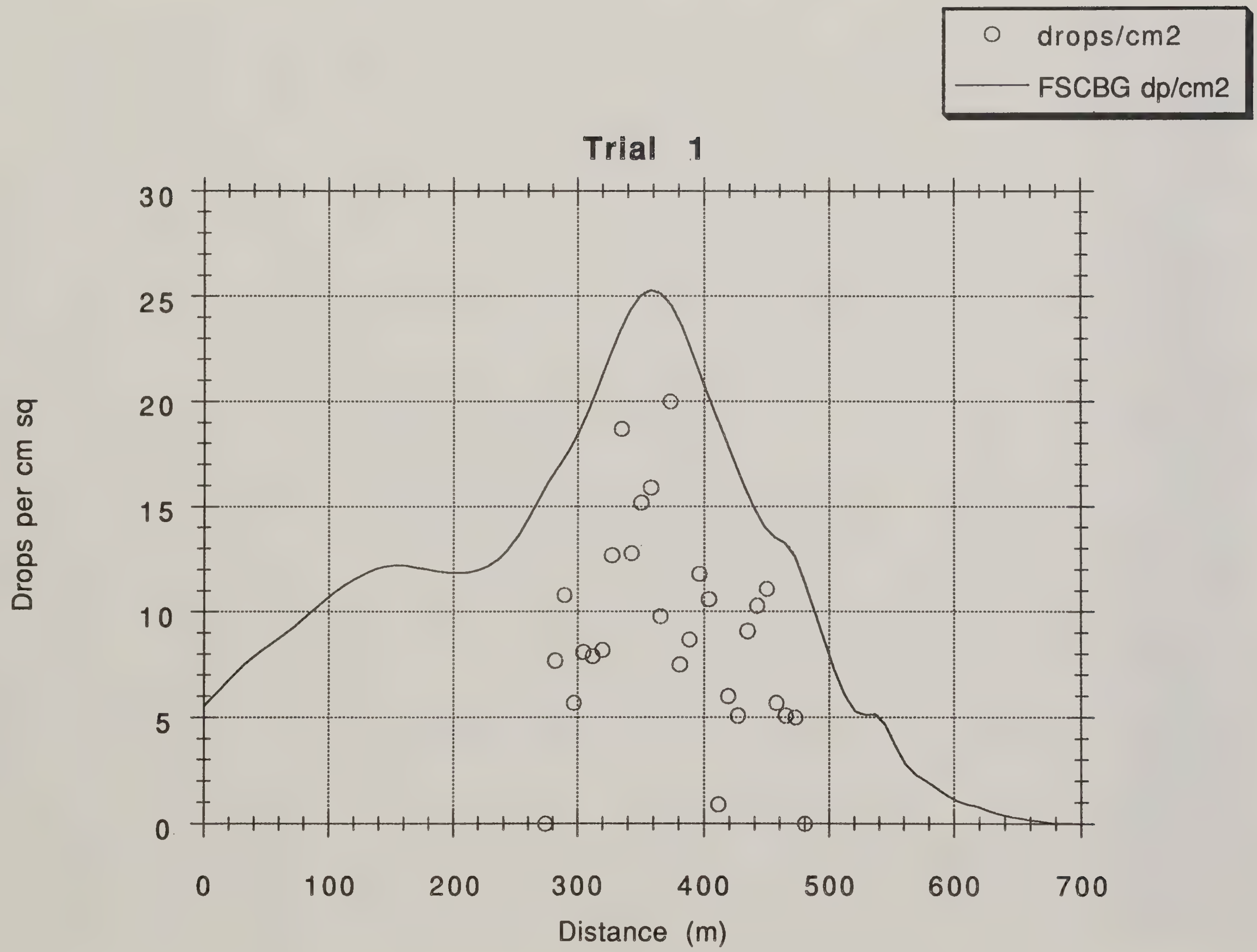
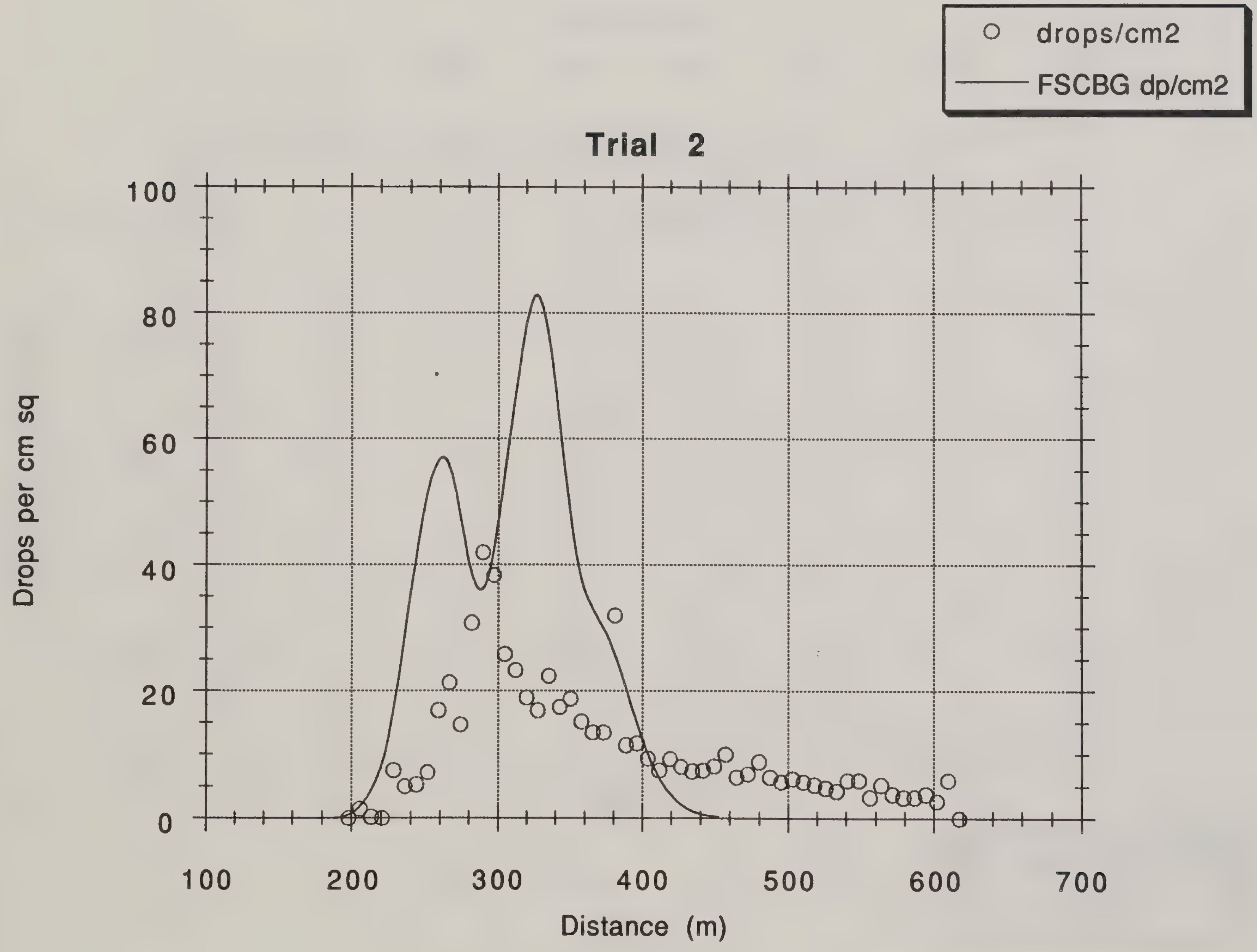
Appendix

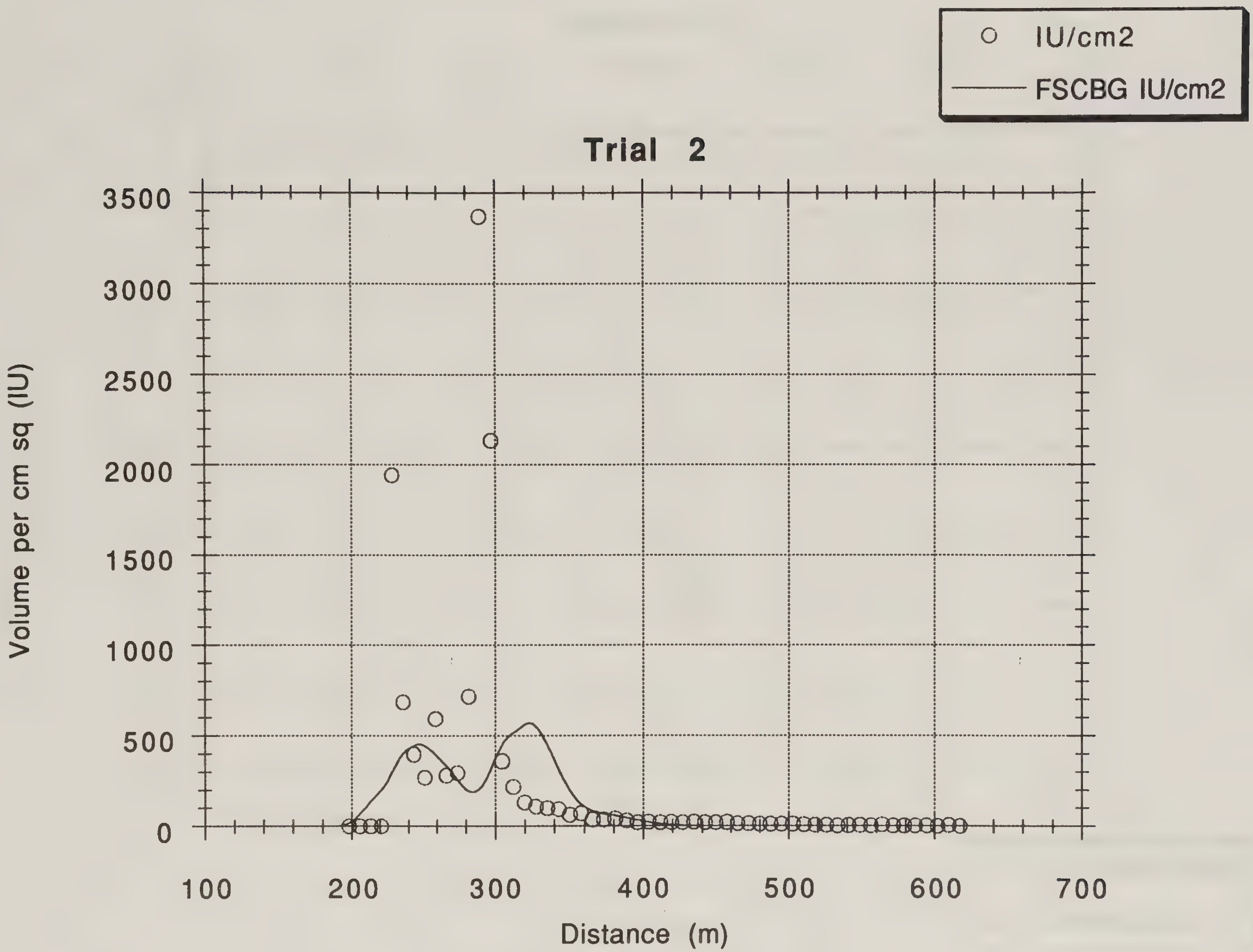
The Appendix contains each of the 25 C-130 spray trials in two plots, first for drops per square centimeter, then for volume (IU) per square centimeter. Data is shown as open circles; FSCBG predictions as solid lines.

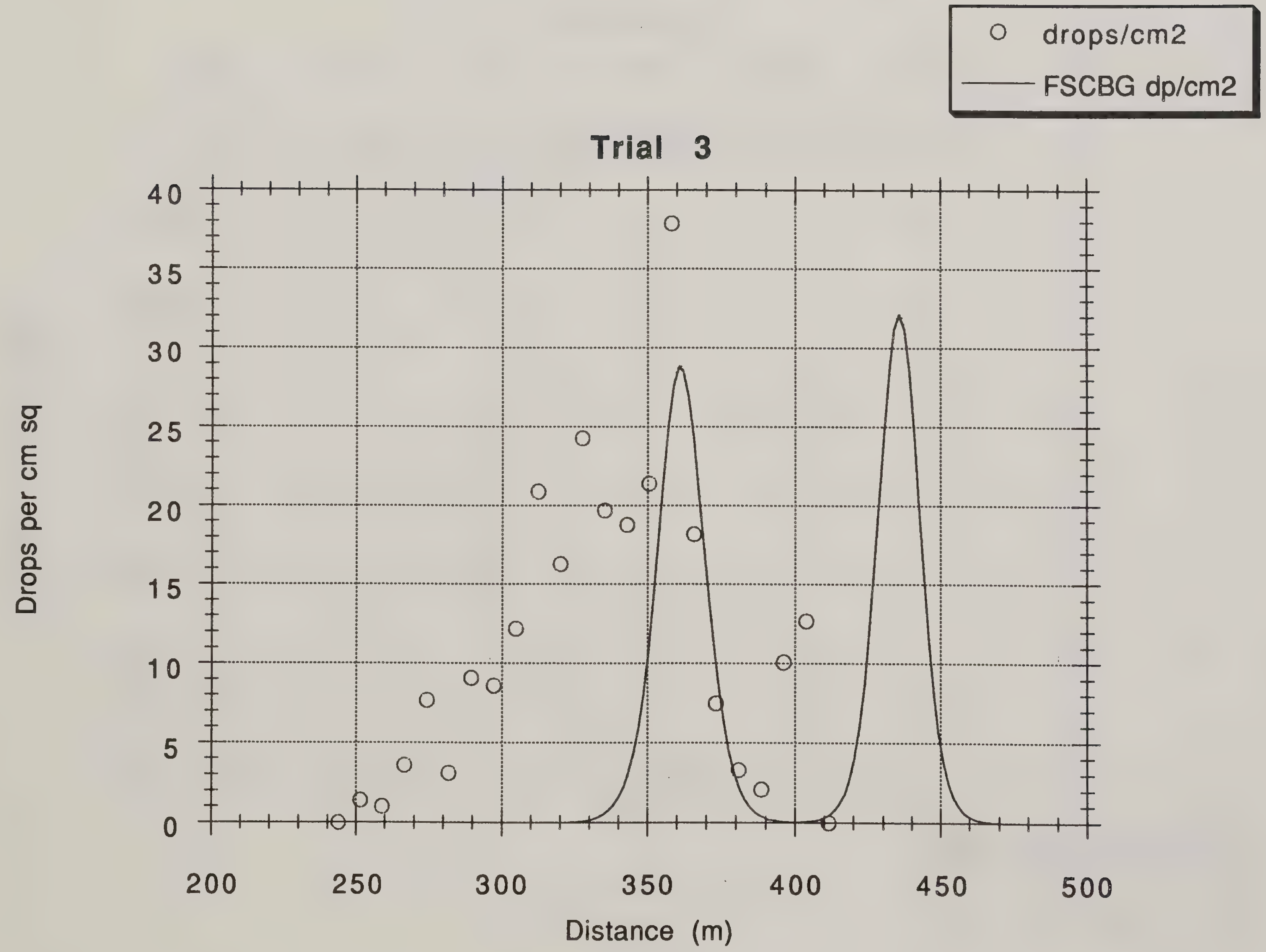

drops/cm2
FSCBG dp/cm2
Trial 1
30
25
20
15
10
5
0
Drops per cm sq
0
100
200
300
400
500
600
700
Distance (m)

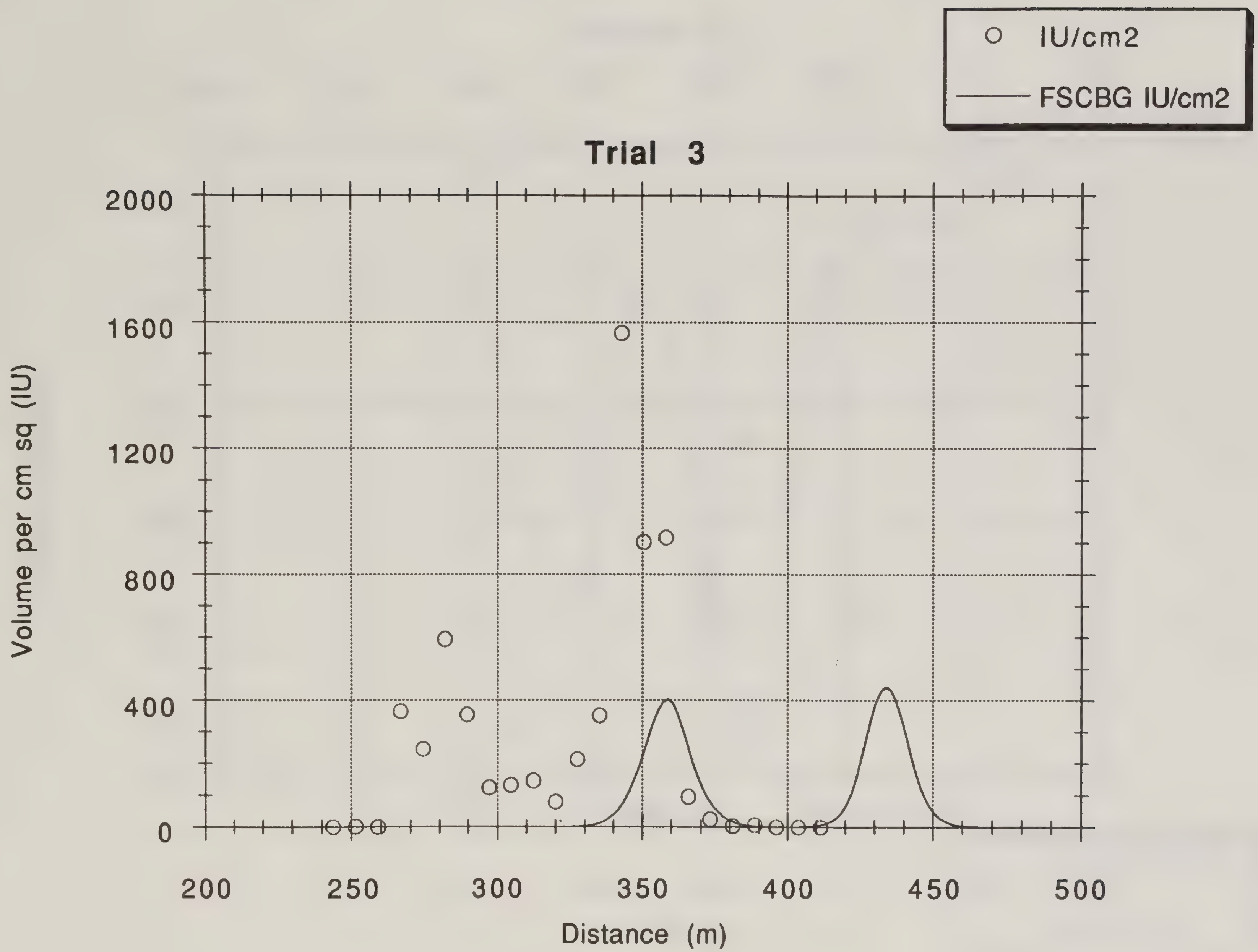
IU/cm2
FSCBG IU/cm2
Trial 1
1200
1000
800
600
400
200
0
Volume per cm sq (IU)
0
100
200
300
400
500
600
700
Distance (m)



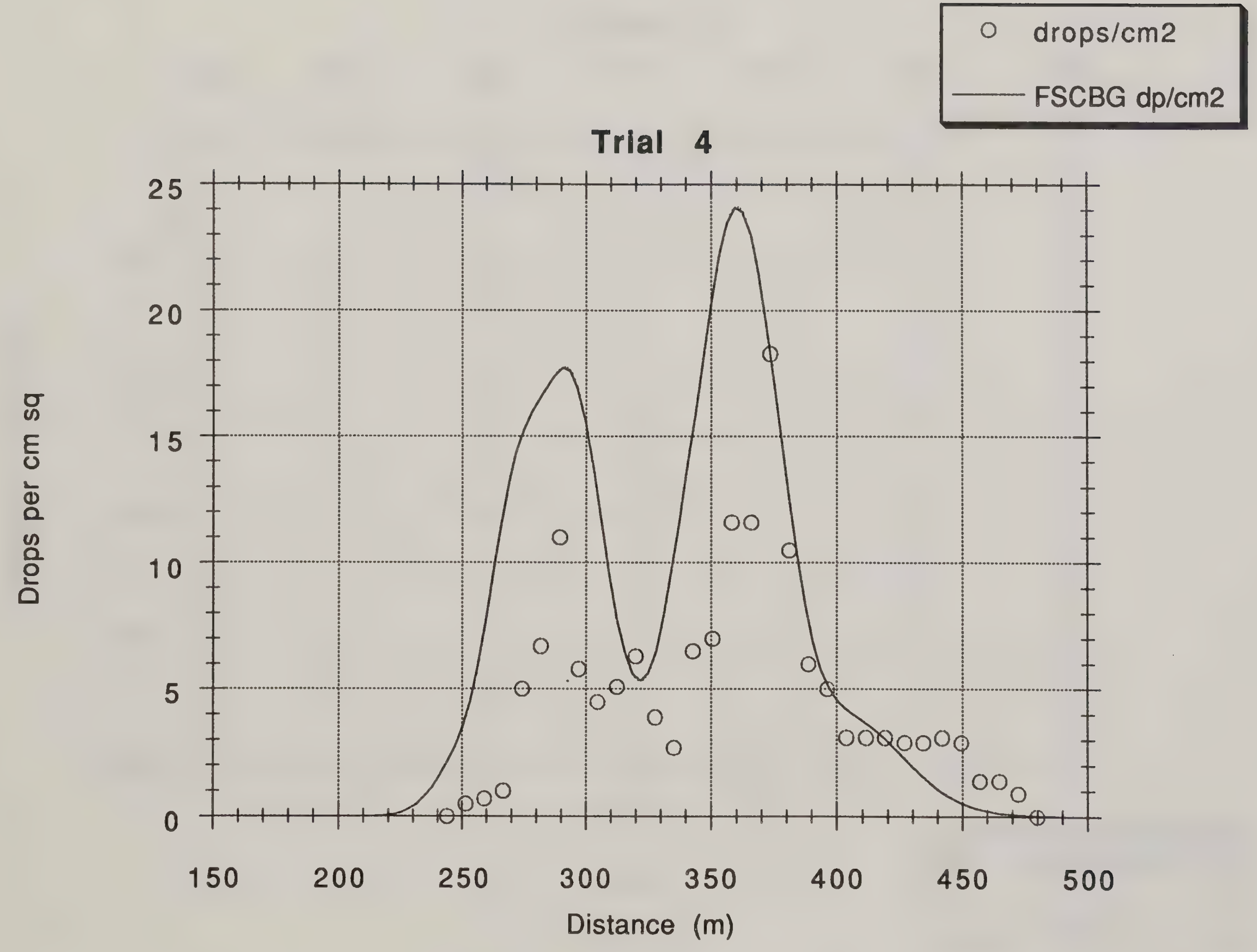
drops/cm2
FSCBG dp/cm2
Trial 2
100
80
60
40
20
0
Drops per cm sq
100
200
300
400
500
600
700
Distance (m)

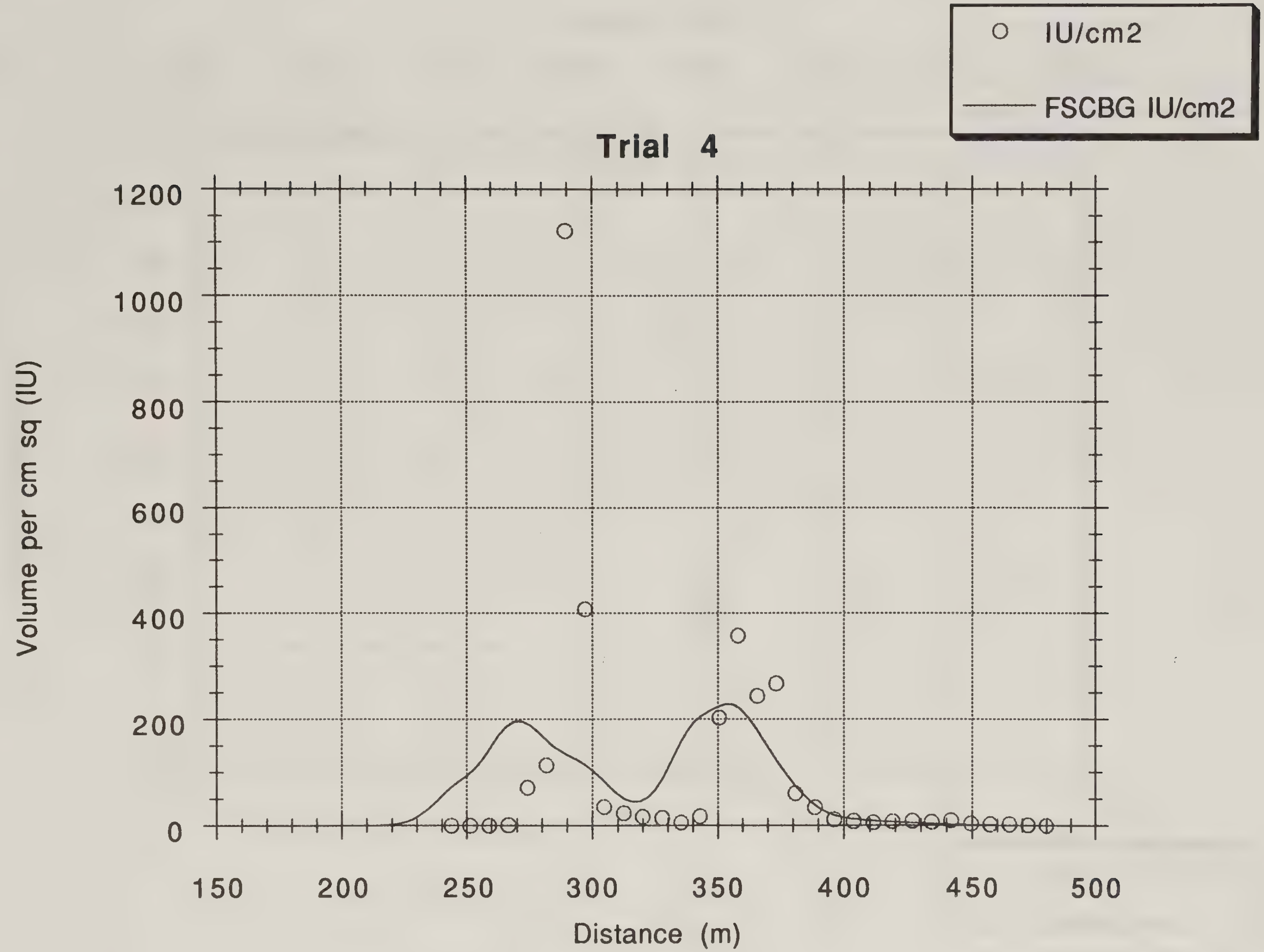

IU/cm2
FSCBG IU/cm2
Trial 2
3500
3000
2500
2000
1500
1000
500
0
Volume per cm sq (IU)
100
200
300
400
500
600
700
Distance (m)


drops/cm2
FSCBG dp/cm2
Trial 3
Drops per cm sq
Distance (m)
0
5
10
15
20
25
30
35
40
200
250
300
350
400
450
500

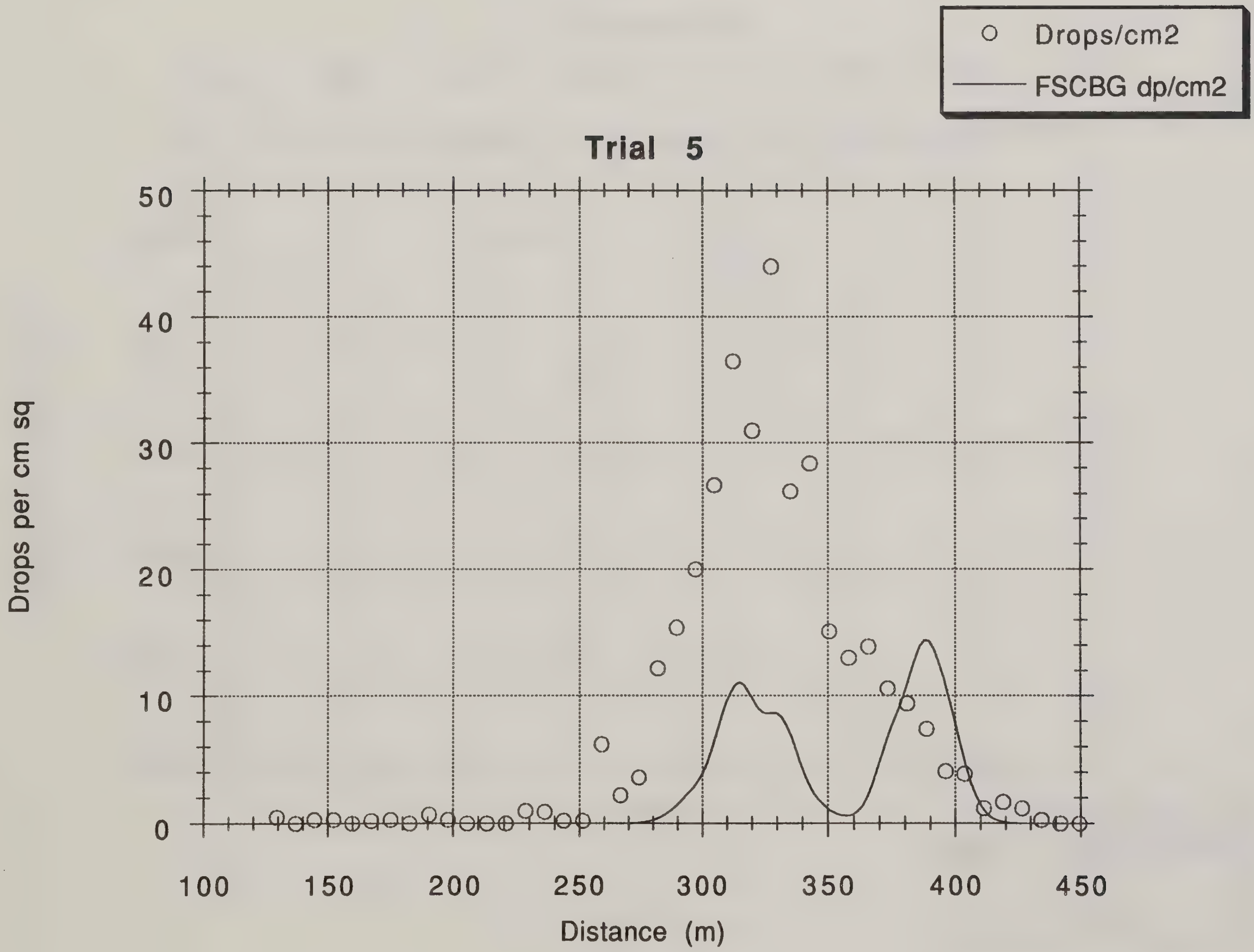


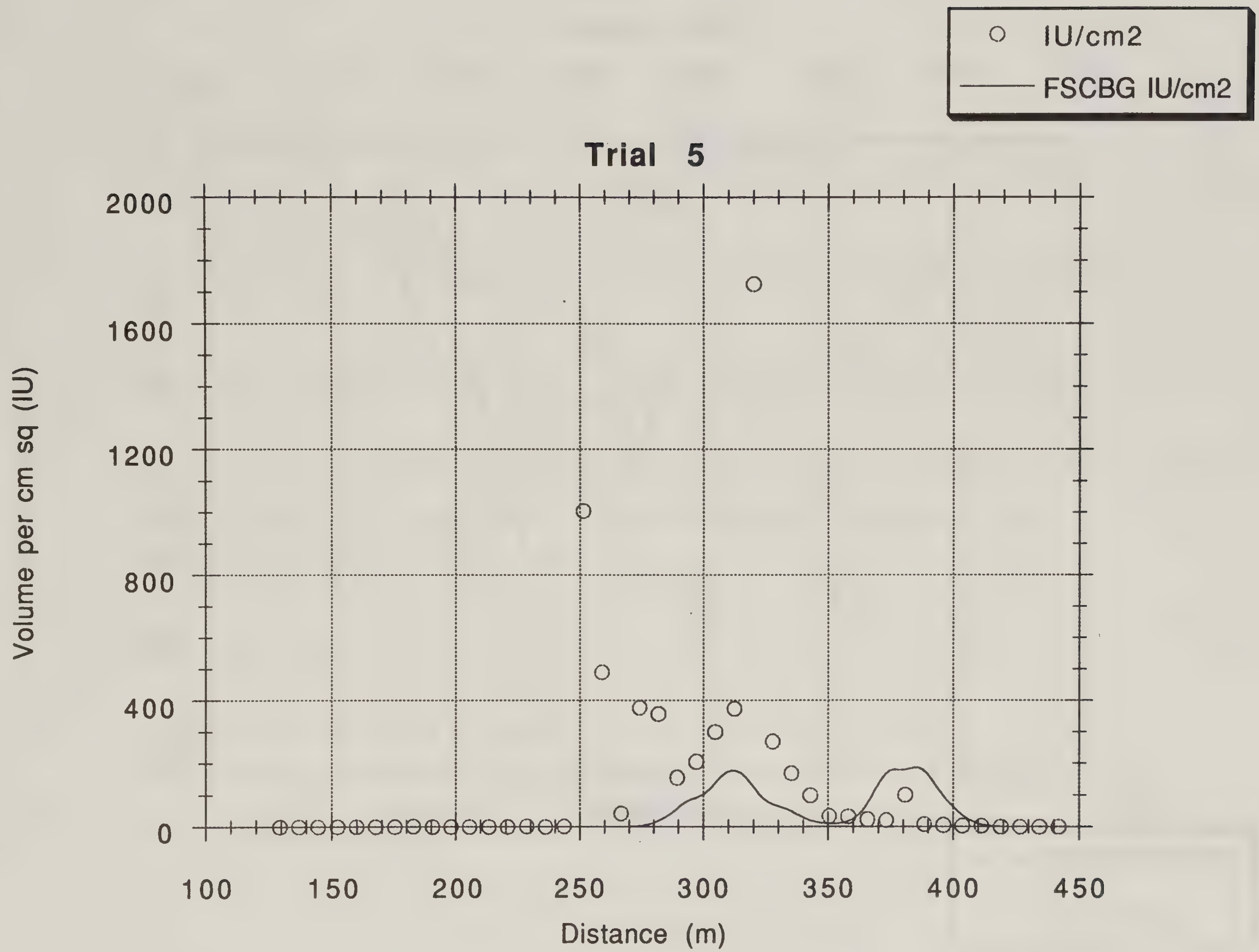
IU/cm2
FSCBG IU/cm2
Trial 3
2000
1600
1200
800
400
0
Volume per cm sq (IU)
200
250
300
350
400
450
500
Distance (m)


Trial 4
drops/cm2
FSCBG dp/cm2
Drops per cm sq
Distance (m)
0
5
10
15
20
25
150
200
250
300
350
400
450
500

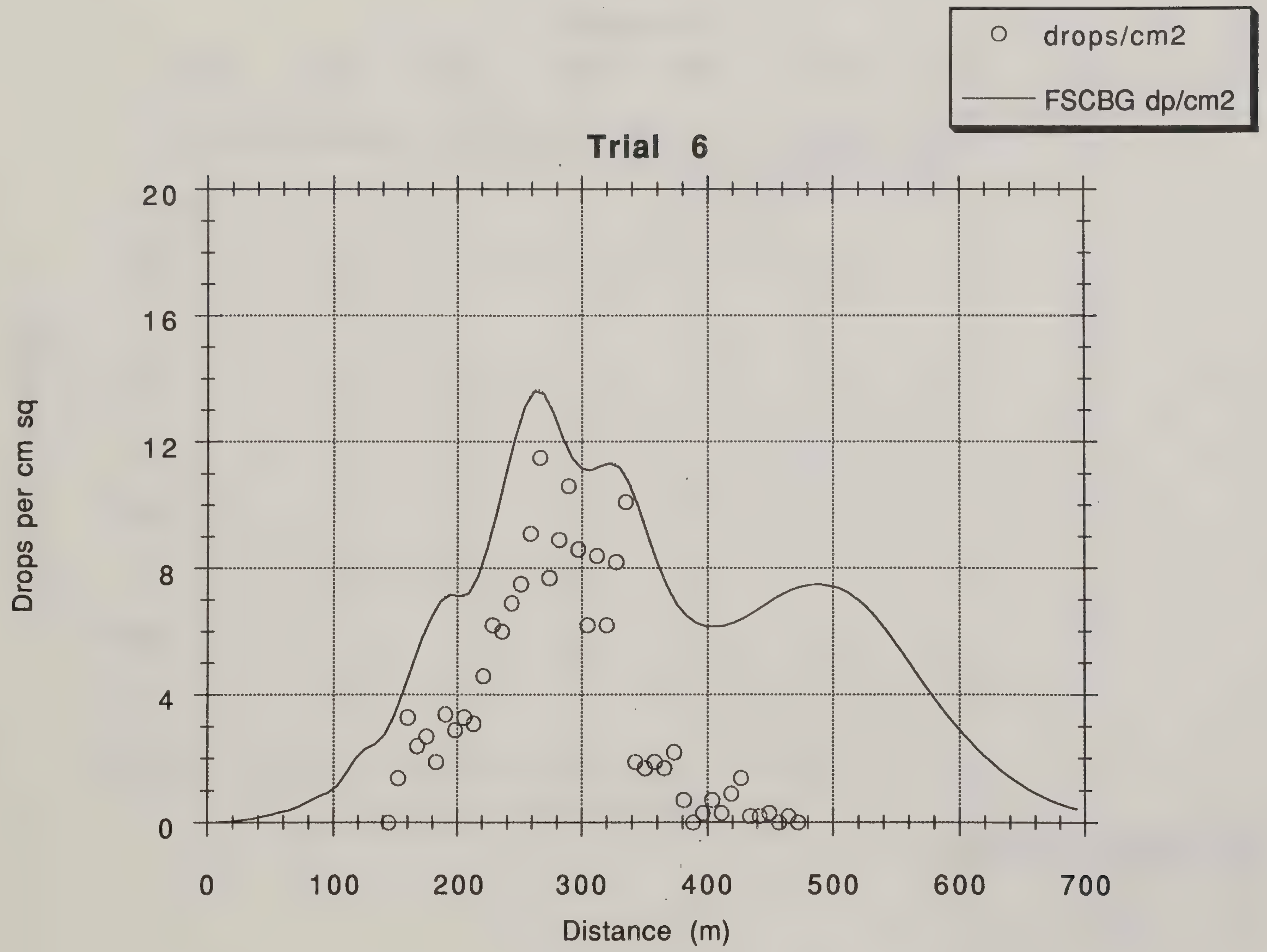


IU/cm2
FSCBG IU/cm2
Trial 4
1200
1000
800
600
400
200
0
Volume per cm sq (IU)
150
200
250
300
350
400
450
500
Distance (m)

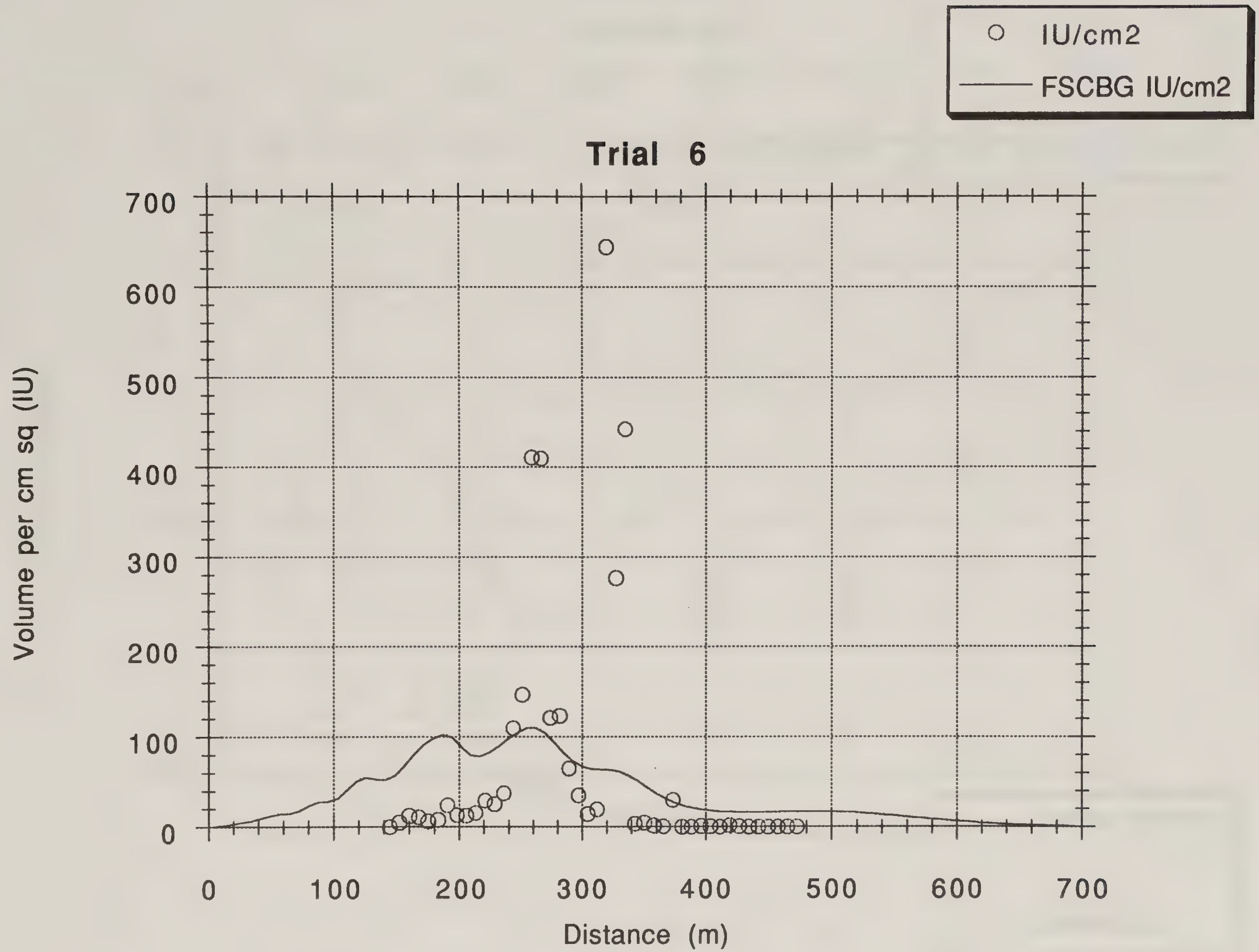

Drops/cm2
FSCBG dp/cm2
Trial 5
Drops per cm sq
Distance (m)
0
10
20
30
40
50
100
150
200
250
300
350
400
450

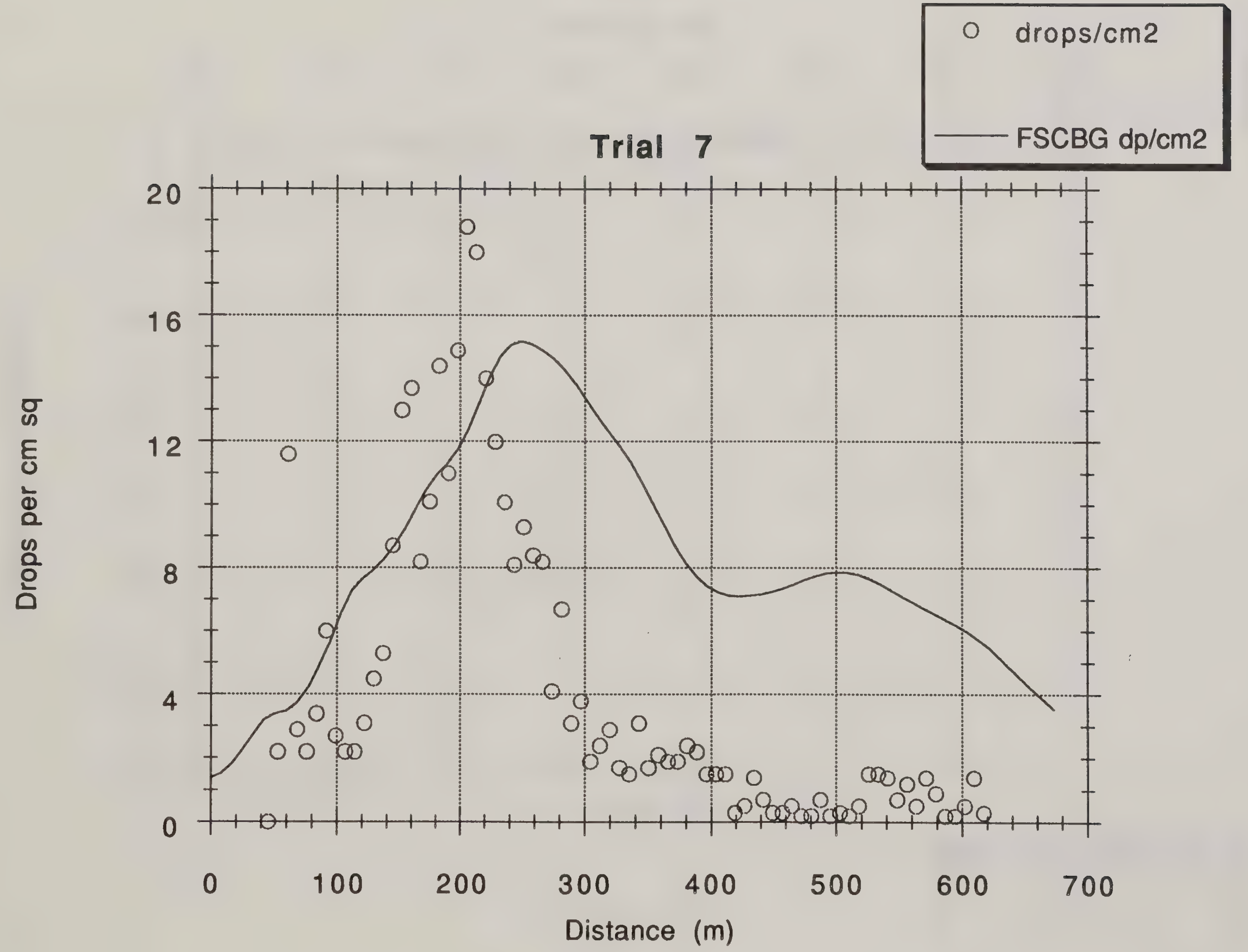


IU/cm2
FSCBG IU/cm2
Trial 5
2000
1600
1200
800
400
0
Volume per cm sq (IU)
100
150
200
250
300
350
400
450
Distance (m)

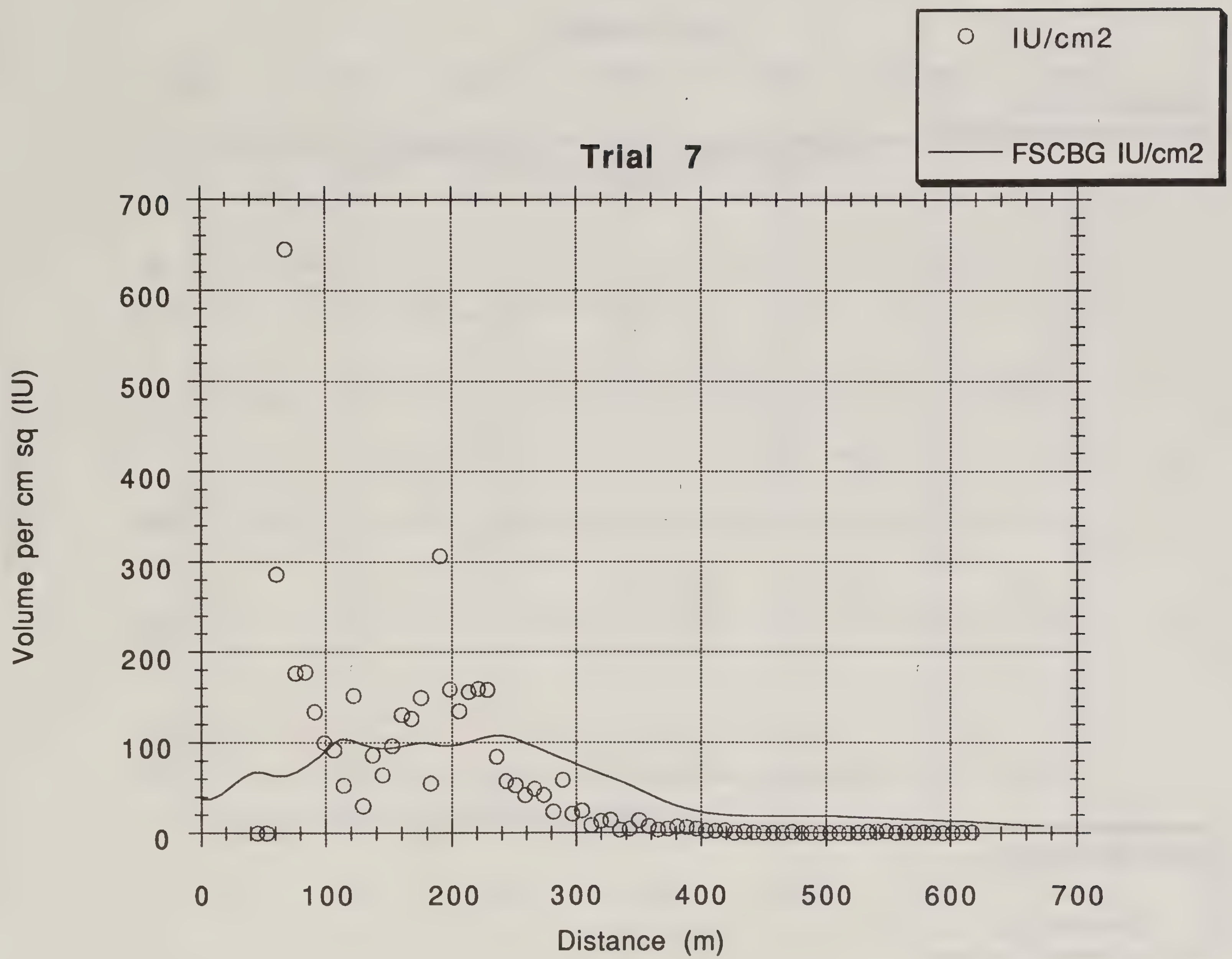


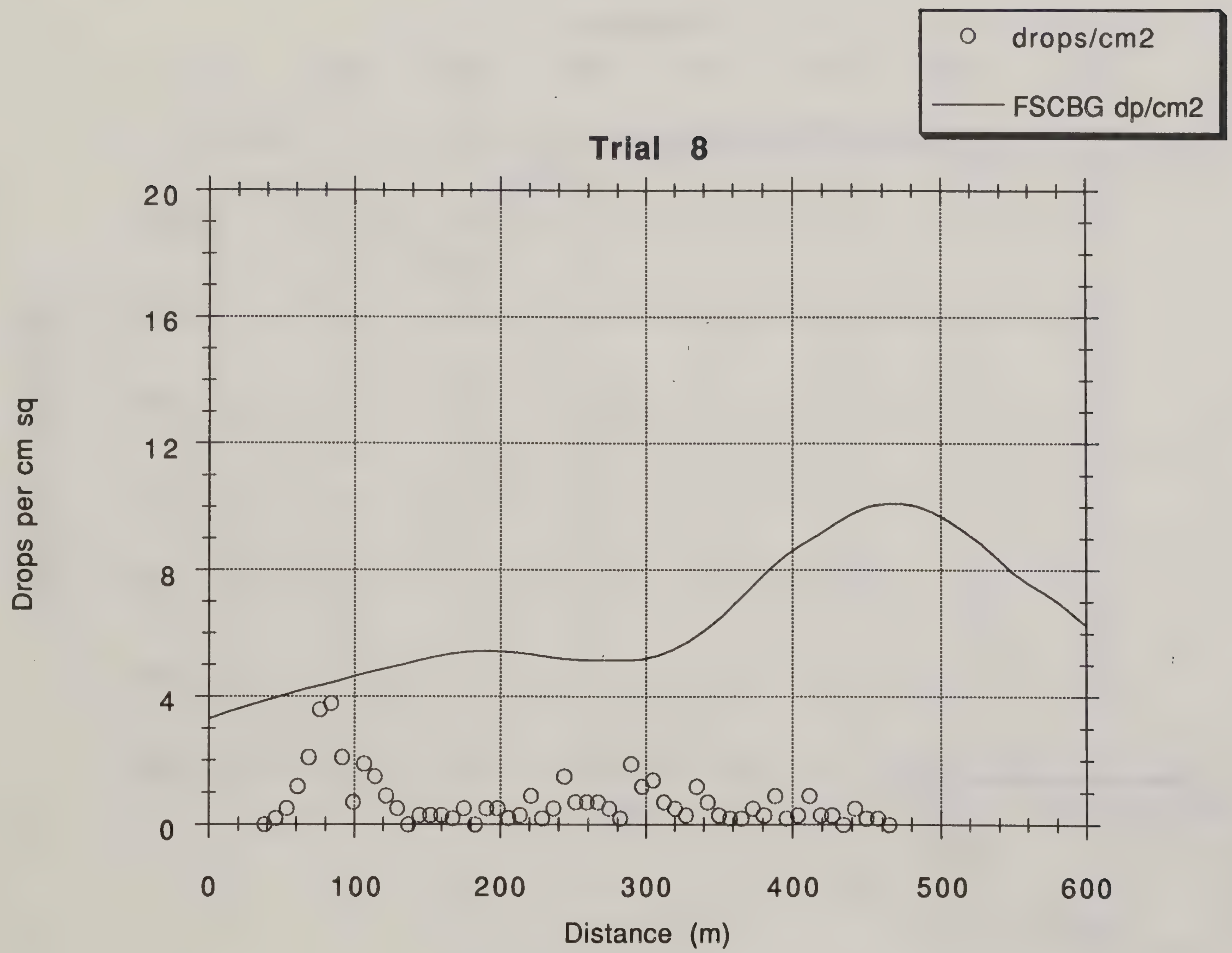
drops/cm2
FSCBG dp/cm2
Trial 6
Drops per cm sq
20
16
12
8
4
0
0
100
200
300
400
500
600
700
Distance (m)


IU/cm2
FSCBG IU/cm2
Trial 6
700
600
500
400
300
200
100
0
Volume per cm sq (IU)
0
100
200
300
400
500
600
700
Distance (m)

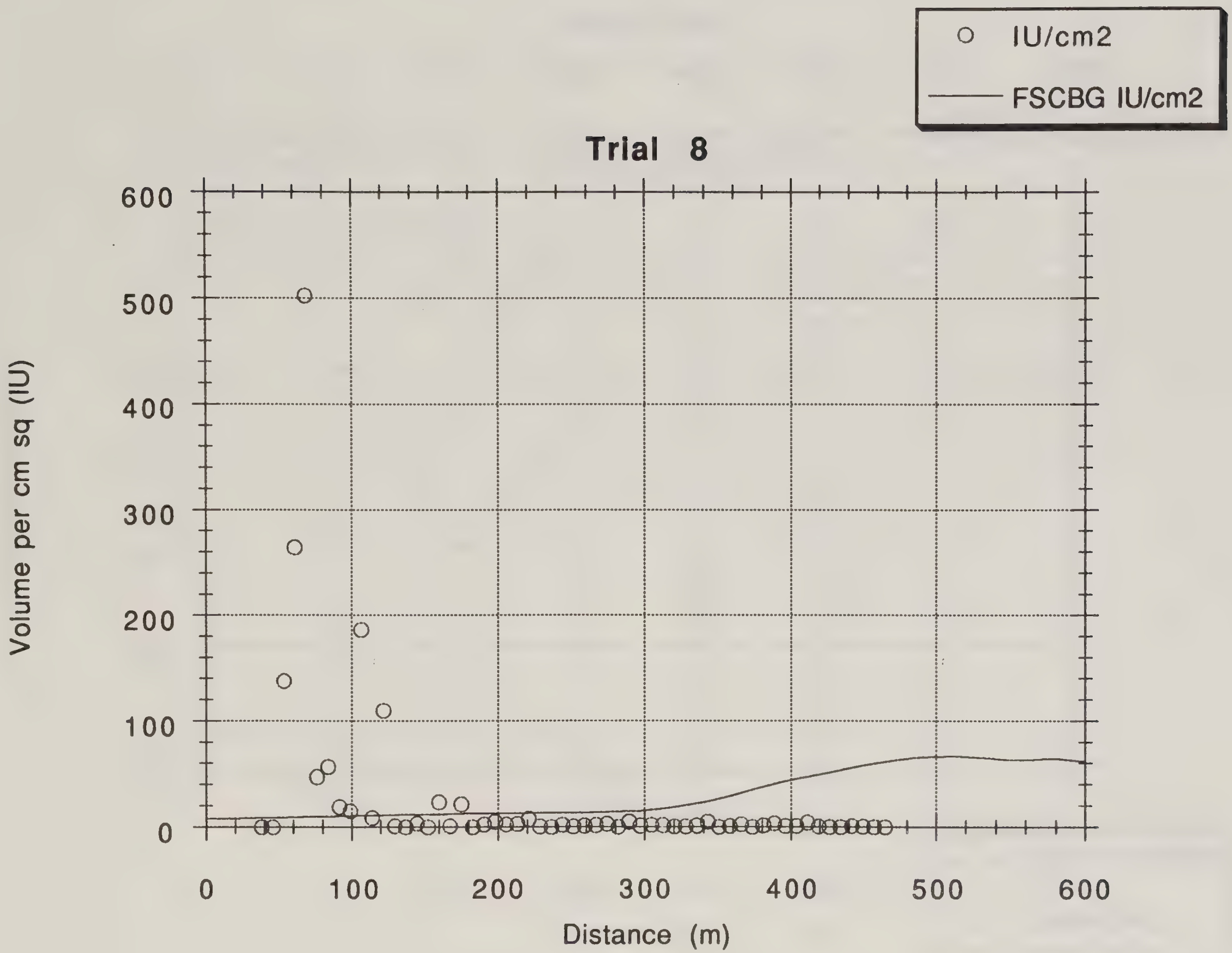


Trial 7
drops/cm2
FSCBG dp/cm2
Drops per cm sq
Distance (m)
0
4
8
12
16
20
0
100
200
300
400
500
600
700

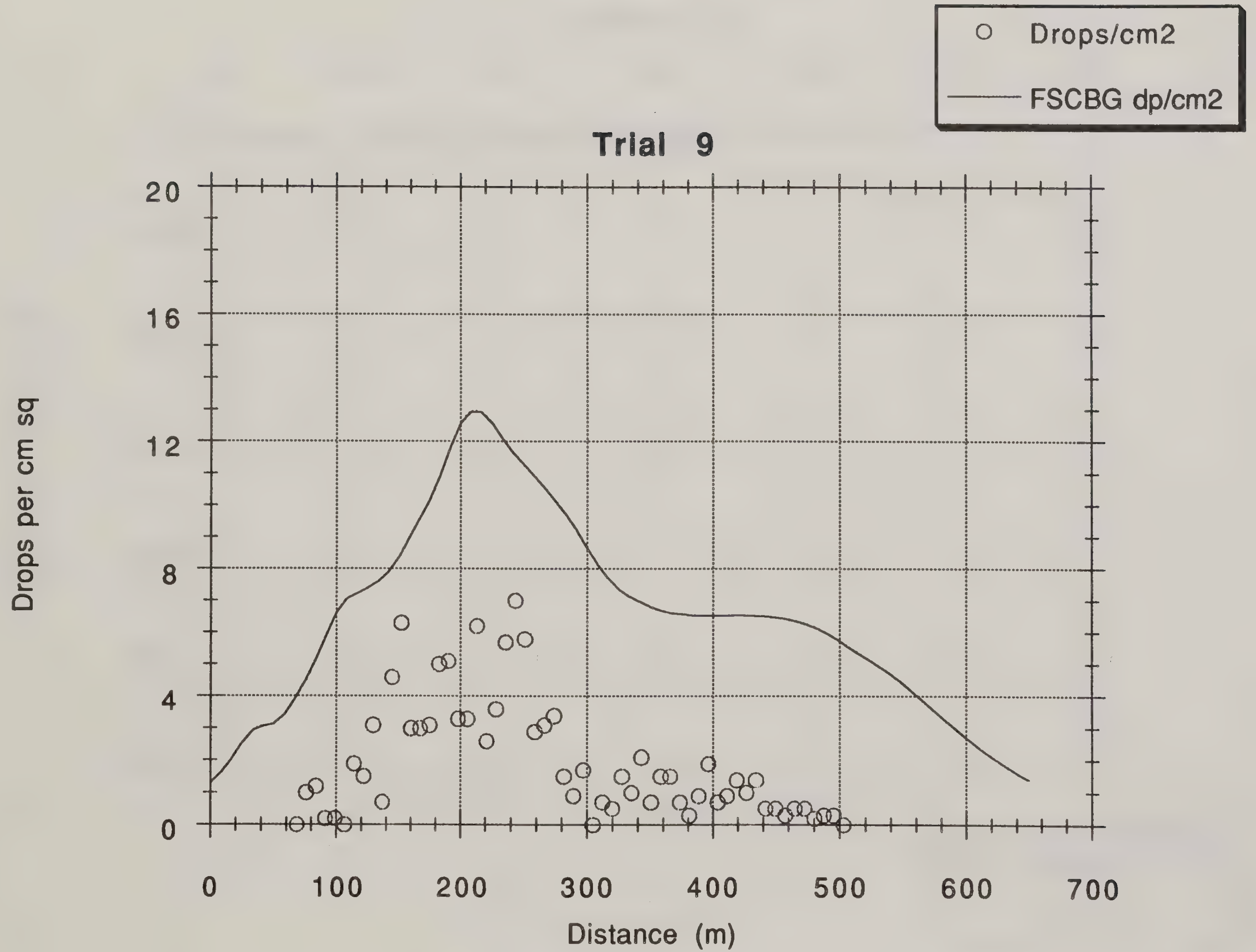

Trial 7
IU/cm2
FSCBG IU/cm2
Volume per cm sq (IU)
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
Distance (m)

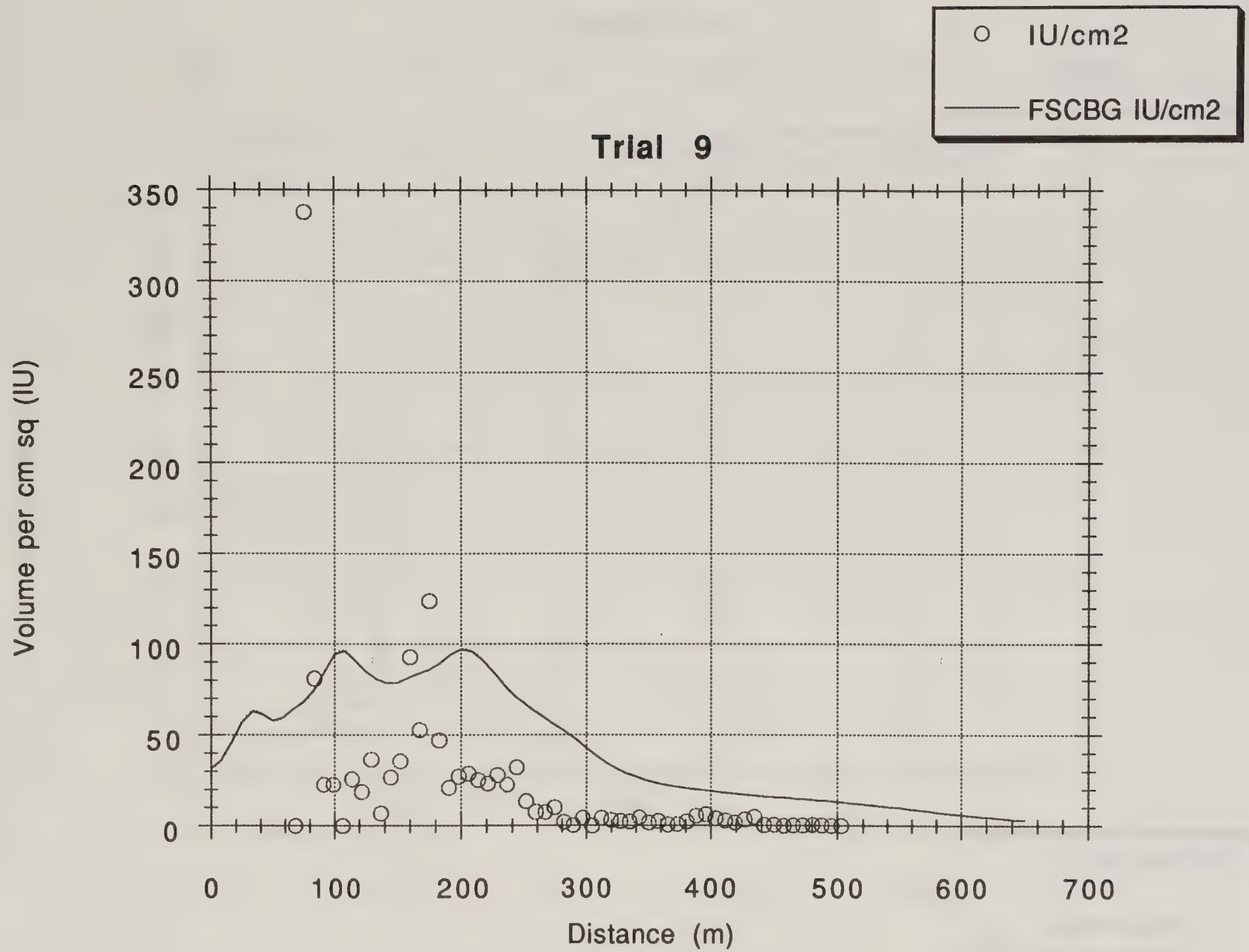


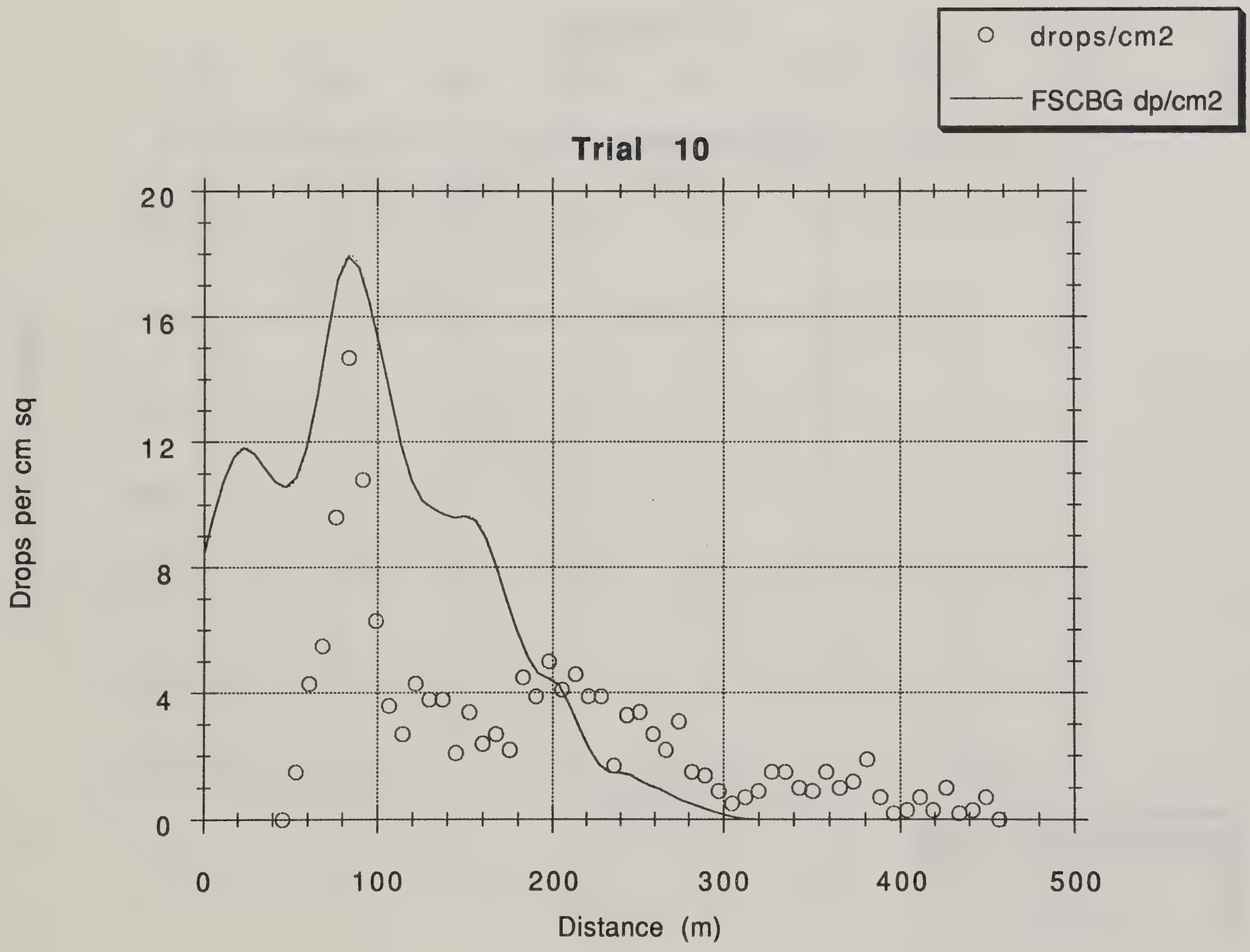
drops/cm2
FSCBG dp/cm2
Trial 8
20
16
12
8
4
0
Drops per cm sq
0
100
200
300
400
500
600
Distance (m)

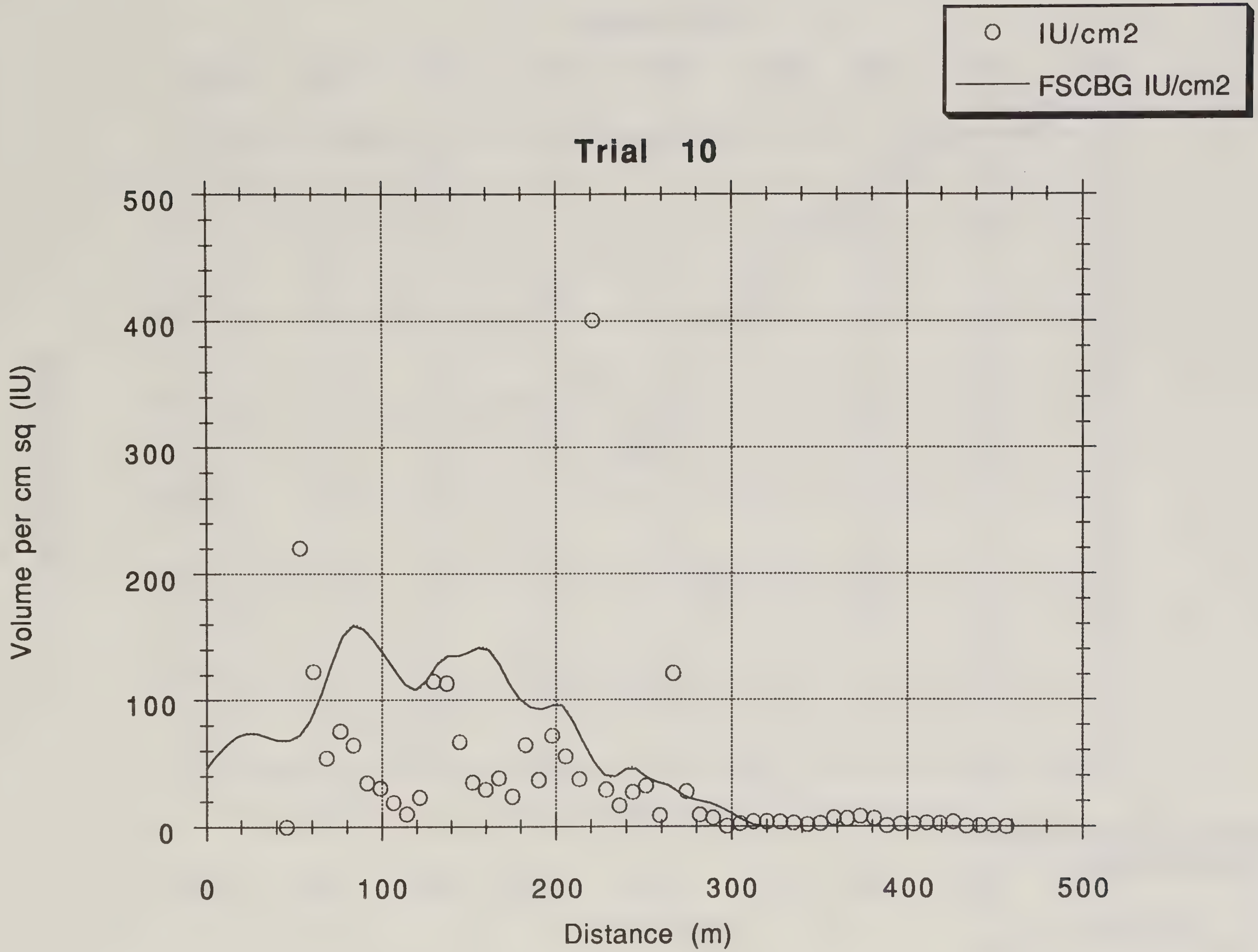


IU/cm2
FSCBG IU/cm2
Trial 8
600
500
400
300
200
100
0
Volume per cm sq (IU)
0
100
200
300
400
500
600
Distance (m)

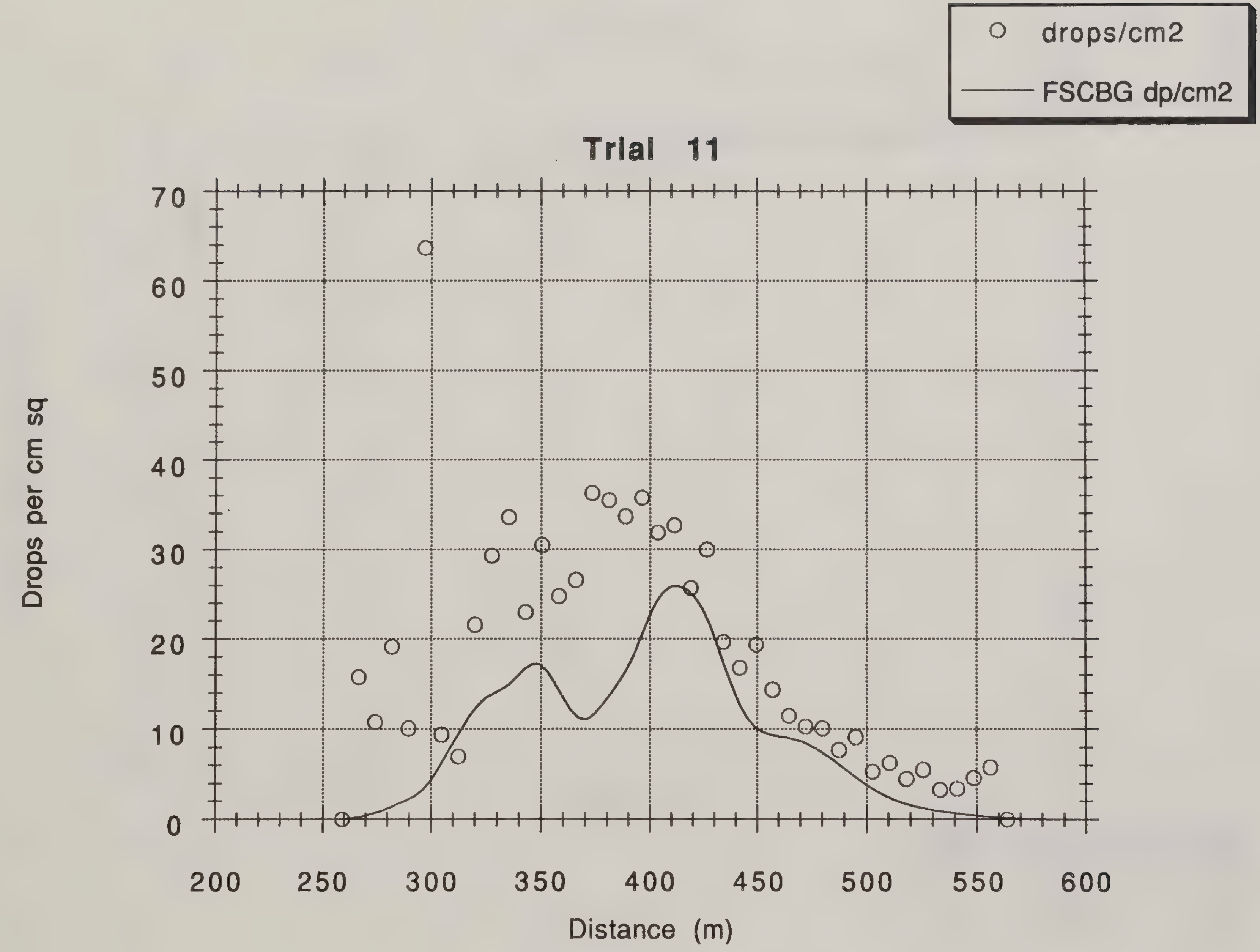

Drops/cm2
FSCBG dp/cm2
Trial 9
20
16
12
8
4
0
0
100
200
300
400
500
600
700
Distance (m)
Drops per cm sq


Trial 9
IU/cm2
FSCBG IU/cm2
Volume per cm sq (IU)
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
700
Distance (m)

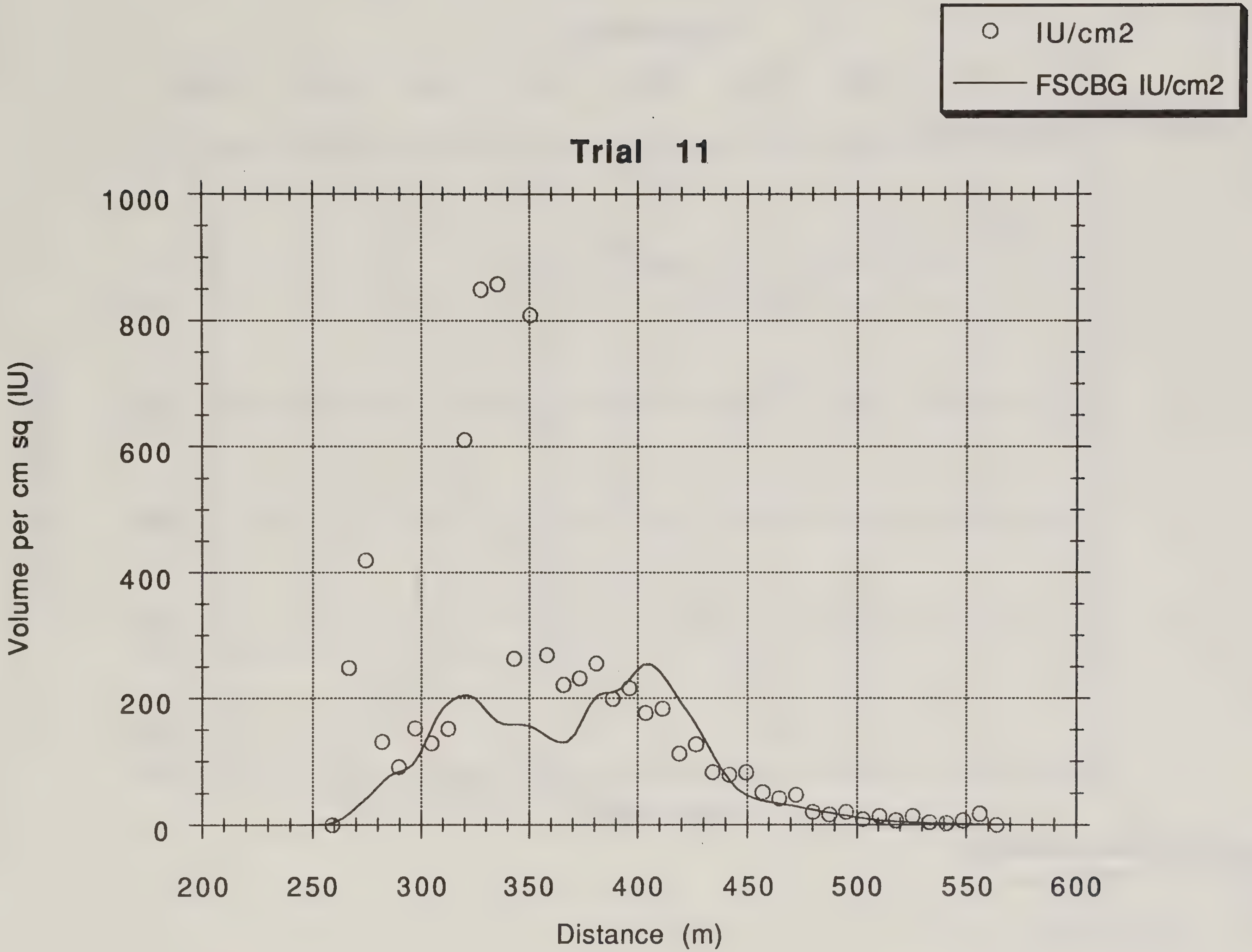

Trial 10
drops/cm2
FSCBG dp/cm2
Drops per cm sq
Distance (m)
0
4
8
12
16
20
0
100
200
300
400
500

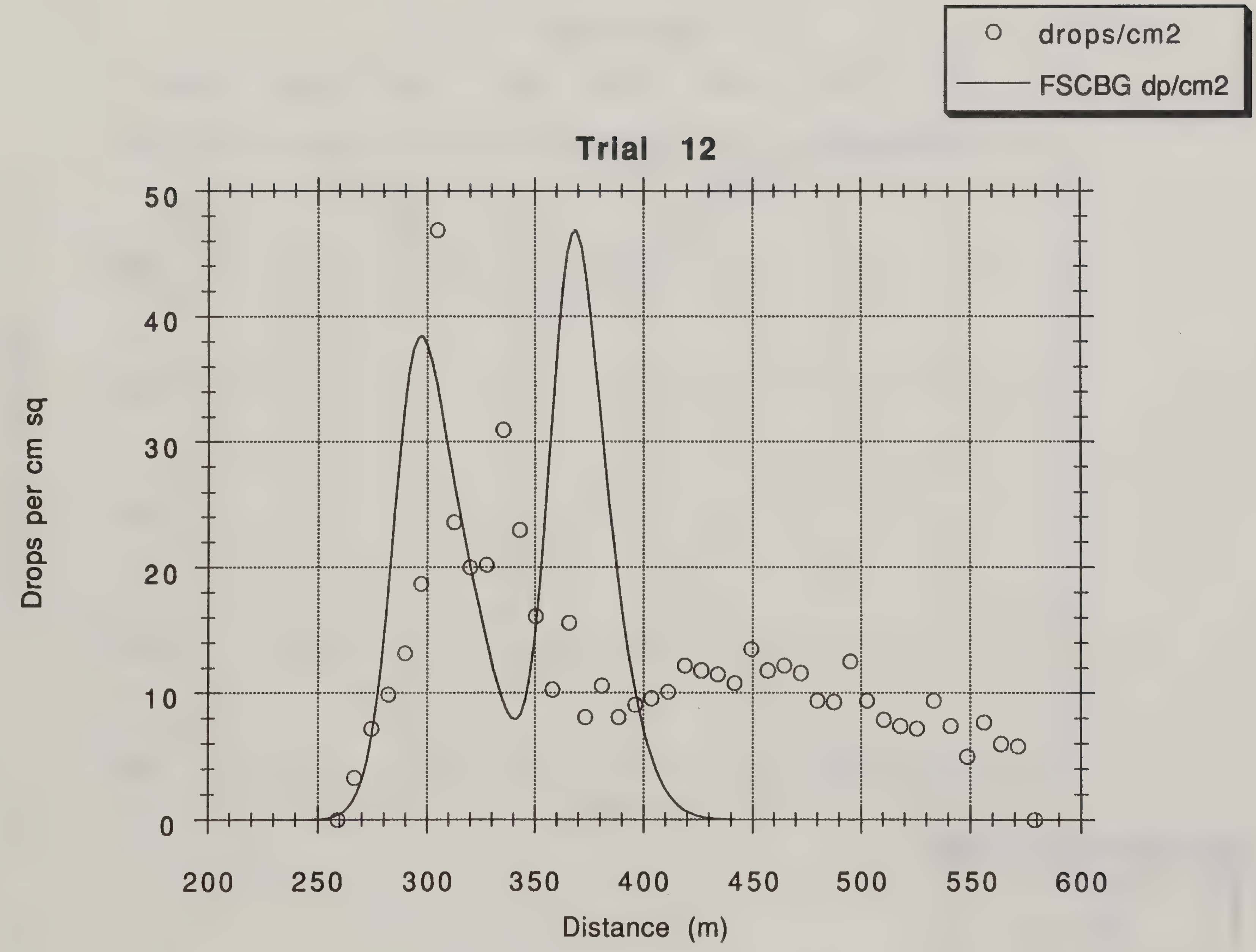


IU/cm2
FSCBG IU/cm2
Trial 10
500
400
300
200
100
0
Volume per cm sq (IU)
0
100
200
300
400
500
Distance (m)

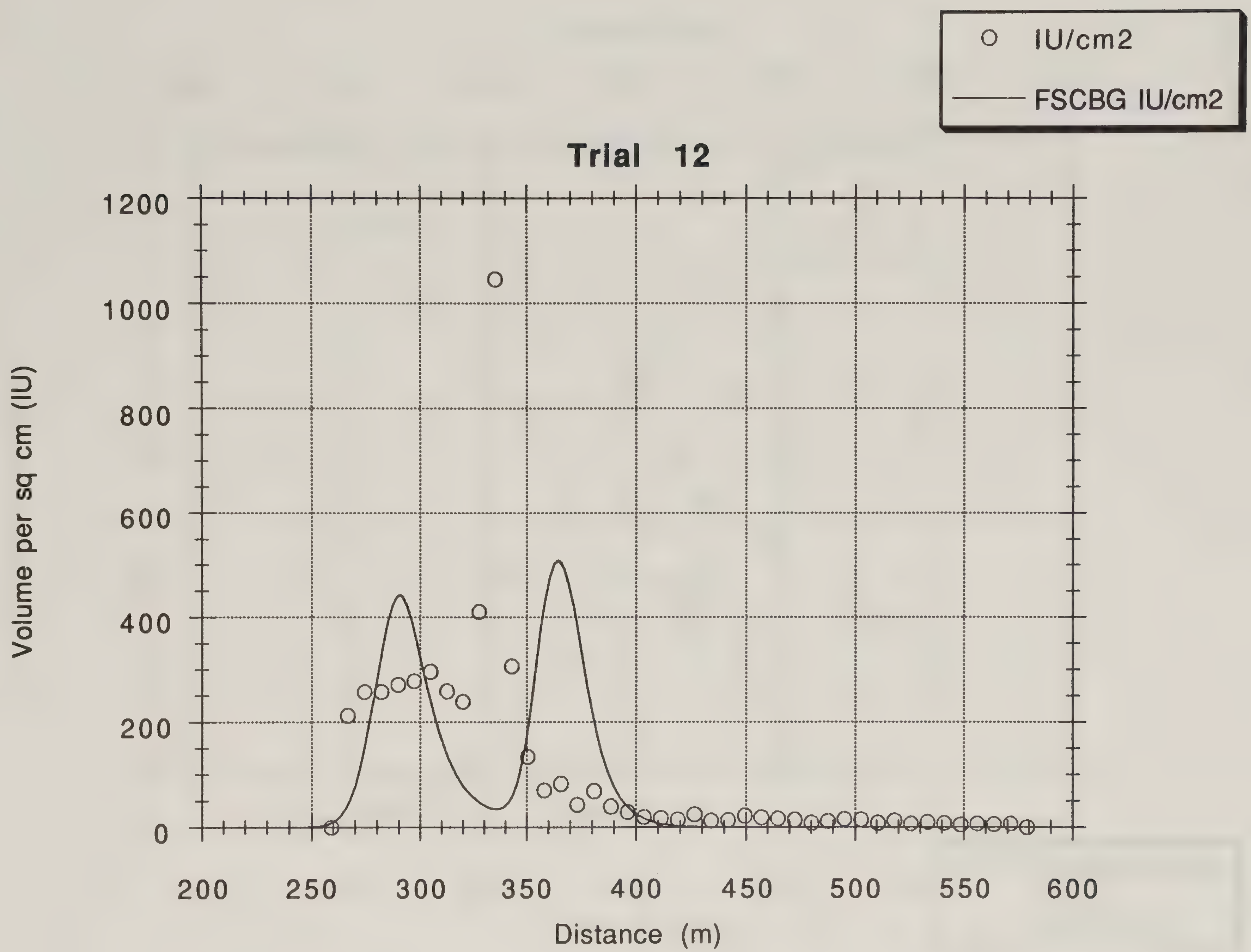


drops/cm2
FSCBG dp/cm2
Trial 11
70
60
50
40
30
20
10
0
Drops per cm sq
200
250
300
350
400
450
500
550
600
Distance (m)

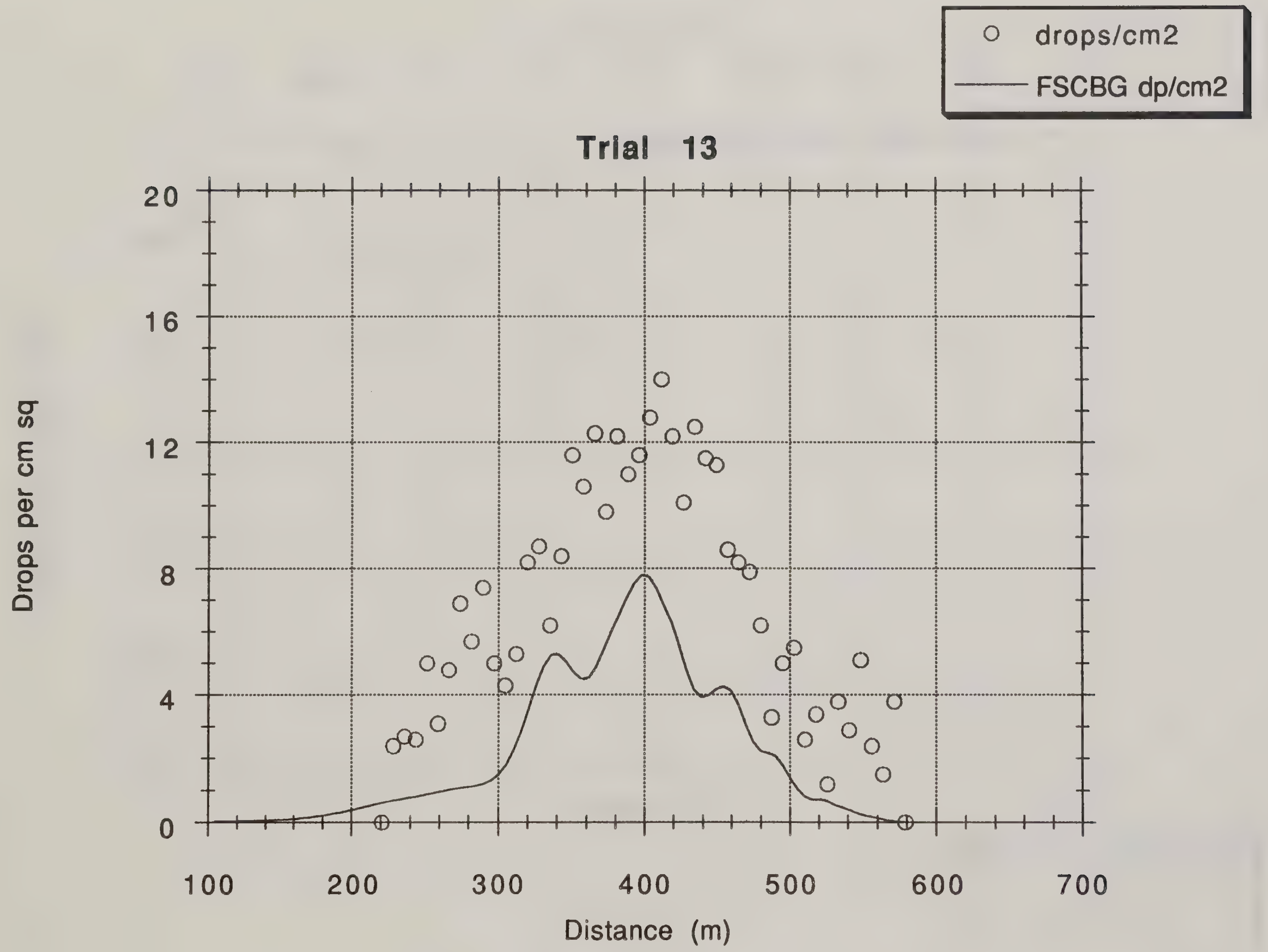

IU/cm2
FSCBG IU/cm2
Trial 11
Volume per cm sq (IU)
0
200
400
600
800
1000
200
250
300
350
400
450
500
550
600
Distance (m)



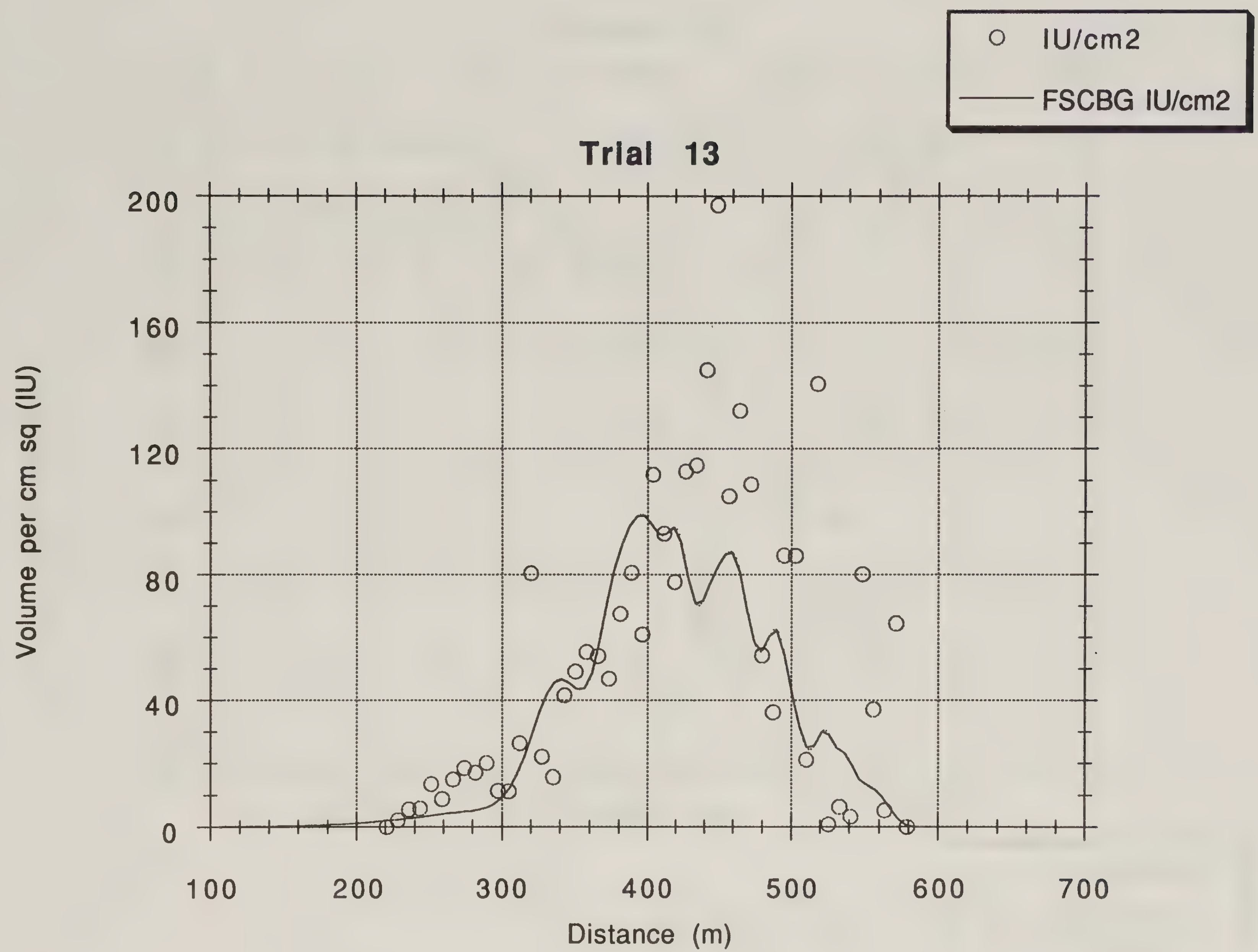
Trial 12
drops/cm2
FSCBG dp/cm2
Drops per cm sq
0
10
20
30
40
50
200
250
300
350
400
450
500
550
600
Distance (m)

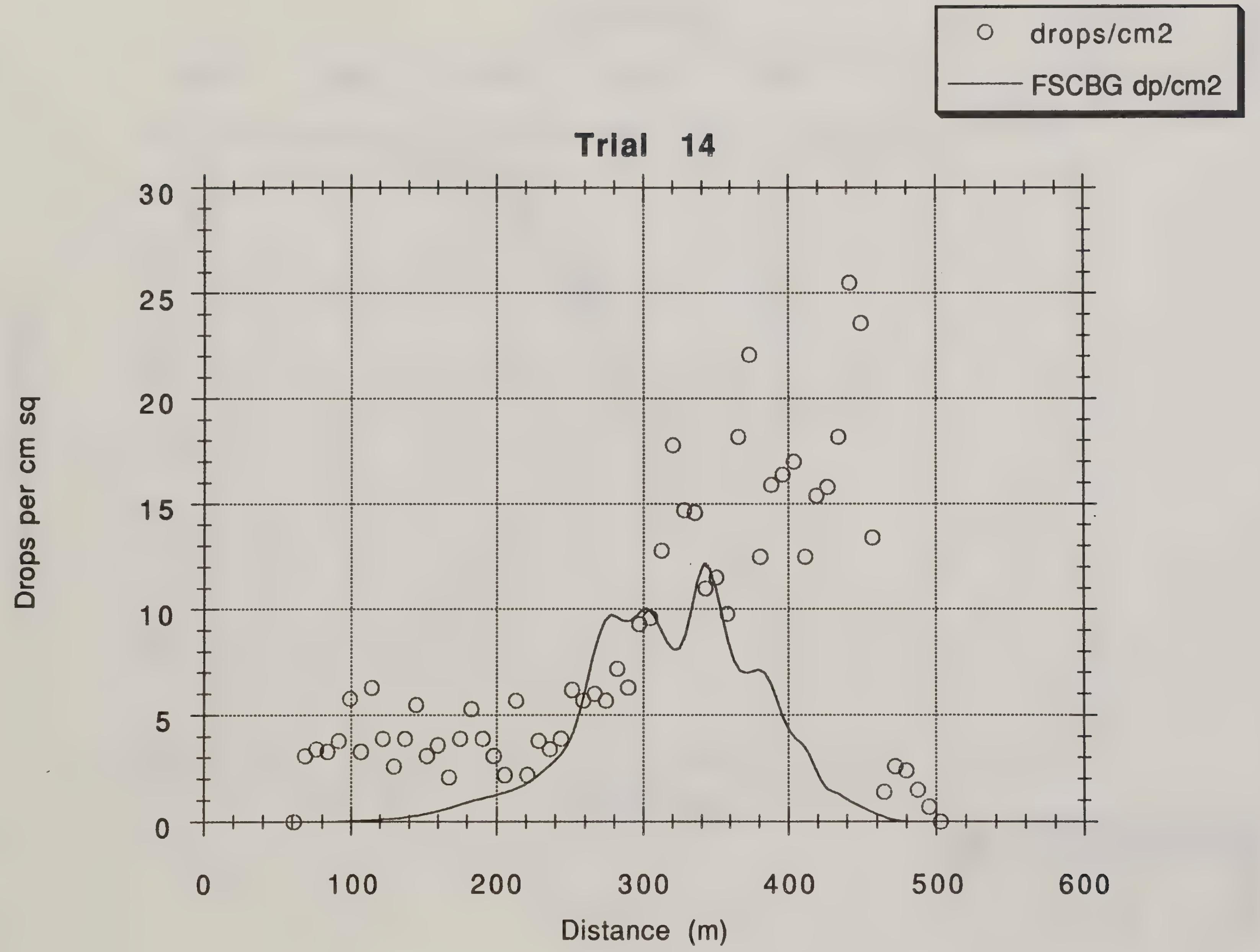


IU/cm2
FSCBG IU/cm2
Trial 12
1200
1000
800
600
400
200
0
200
250
300
350
400
450
500
550
600
Distance (m)
Volume per sq cm (IU)

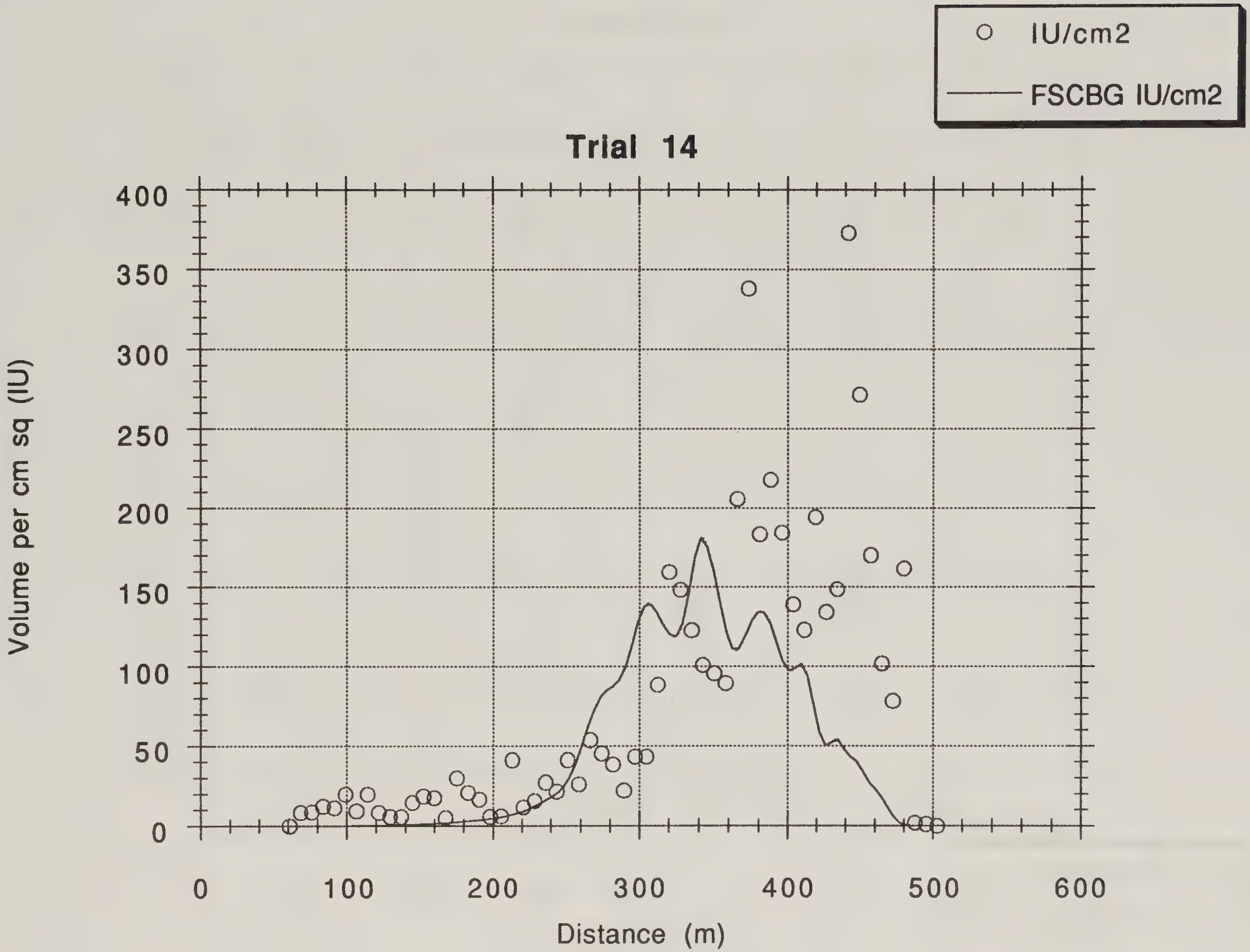


drops/cm2
FSCBG dp/cm2
Trial 13
20
16
12
8
4
0
Drops per cm sq
100
200
300
400
500
600
700
Distance (m)

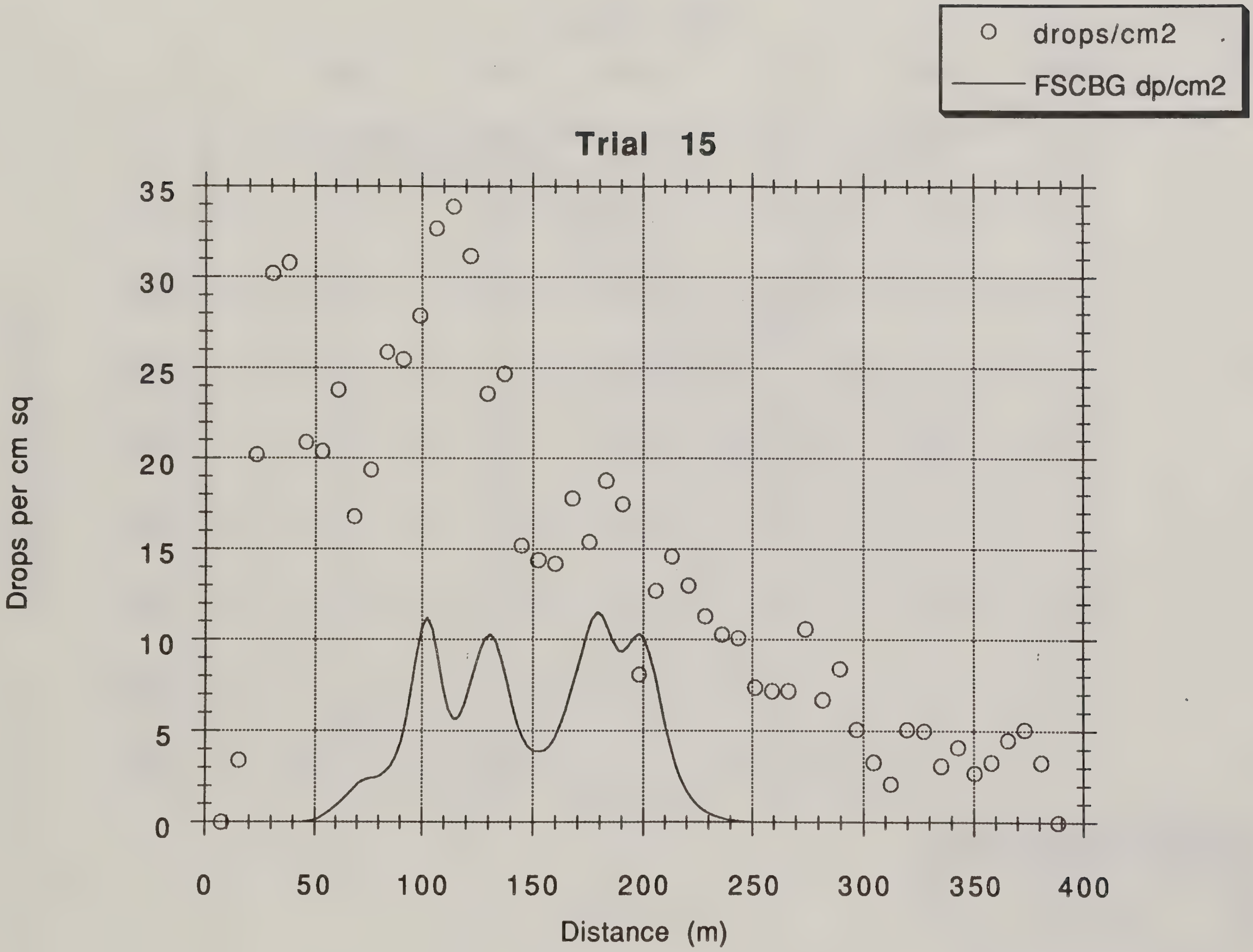

Trial 13
IU/cm2
FSCBG IU/cm2
Volume per cm sq (IU)
Distance (m)
200
160
120
80
40
0
100
200
300
400
500
600
700



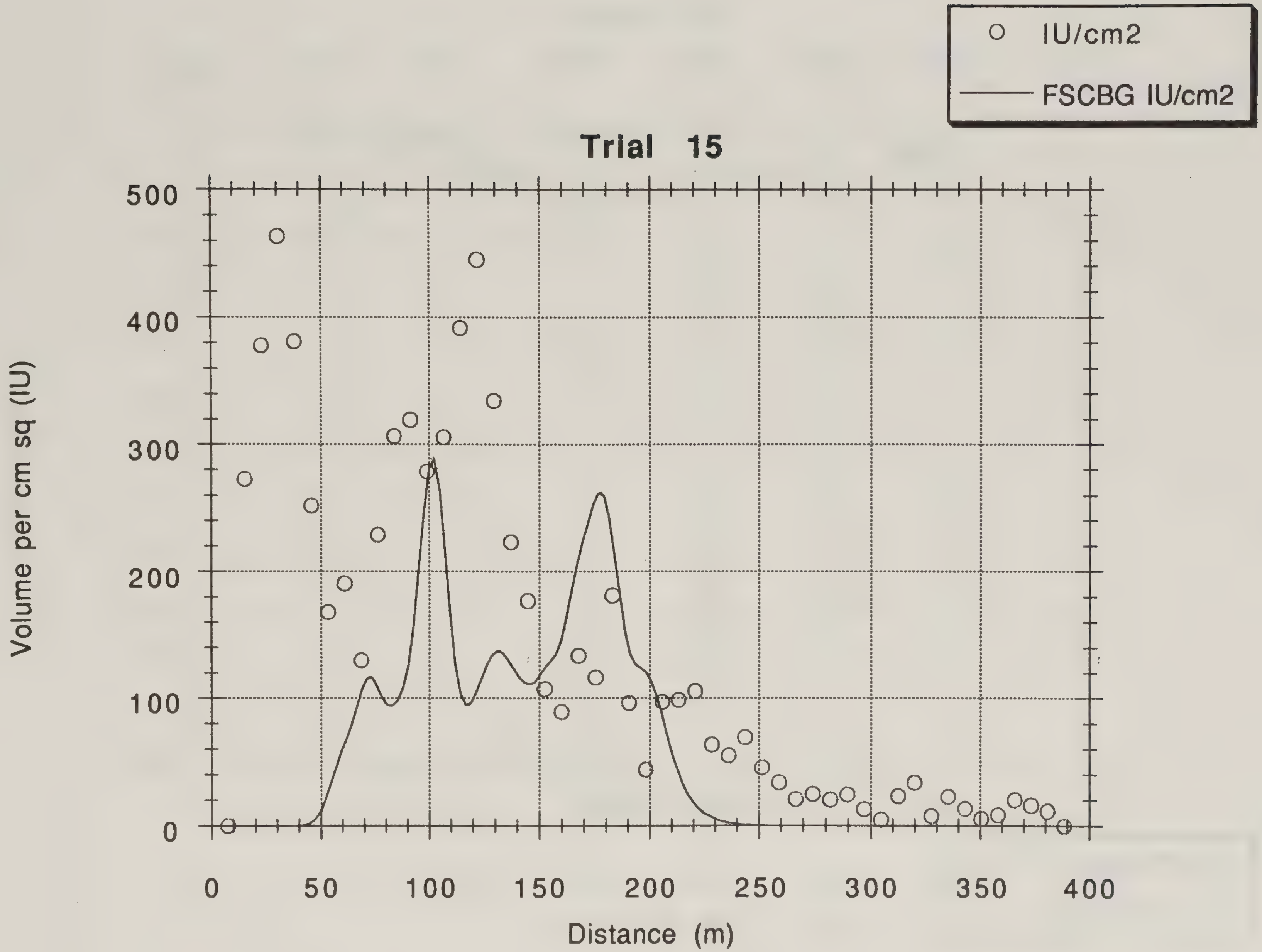
drops/cm2
FSCBG dp/cm2
Trial 14
30
25
20
15
10
5
0
0
100
200
300
400
500
600
Drops per cm sq
Distance (m)



Trial 14
IU/cm2
FSCBG IU/cm2
Volume per cm sq (IU)
0
50
100
150
200
250
300
350
400
0
100
200
300
400
500
600
Distance (m)

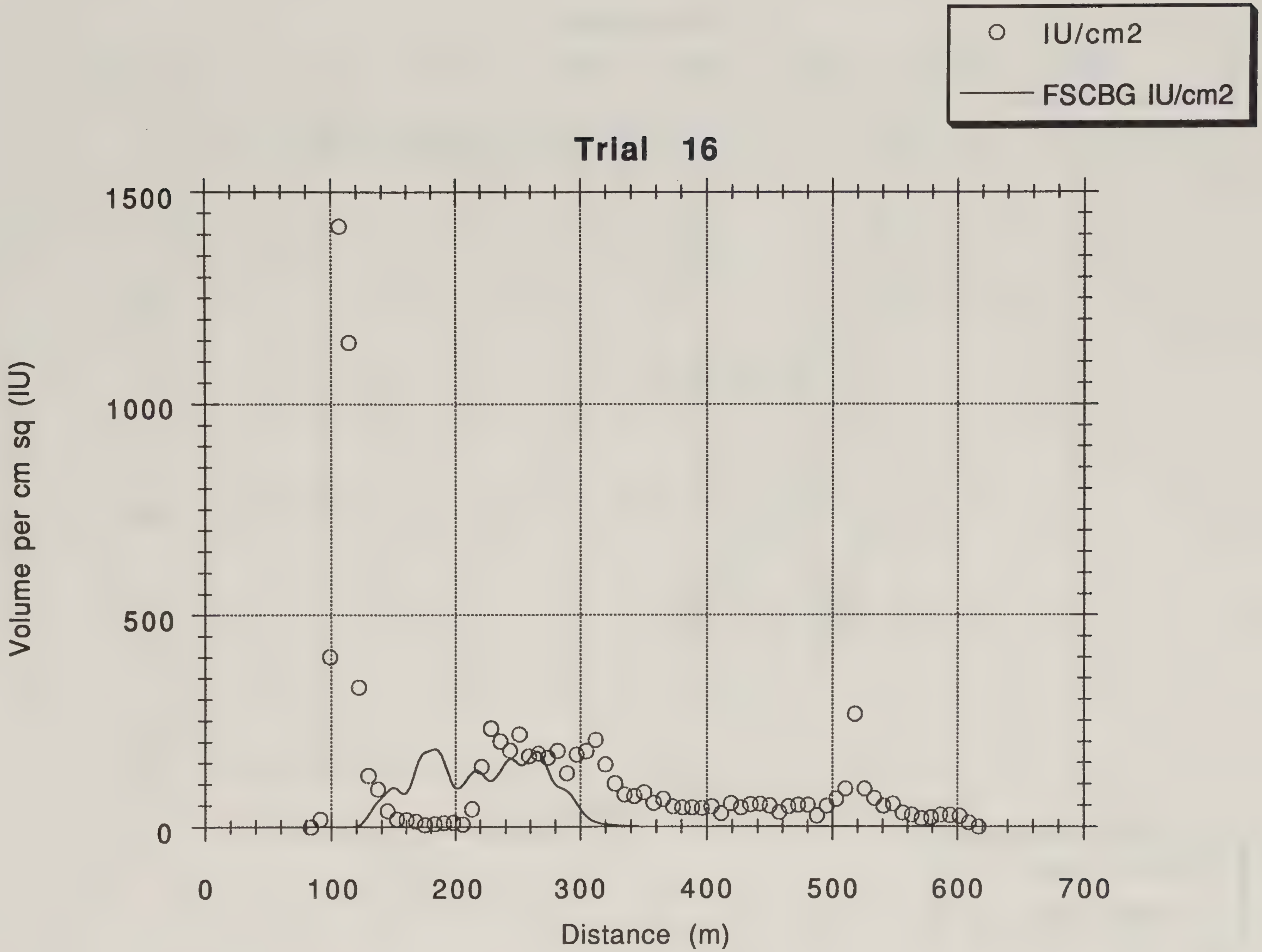


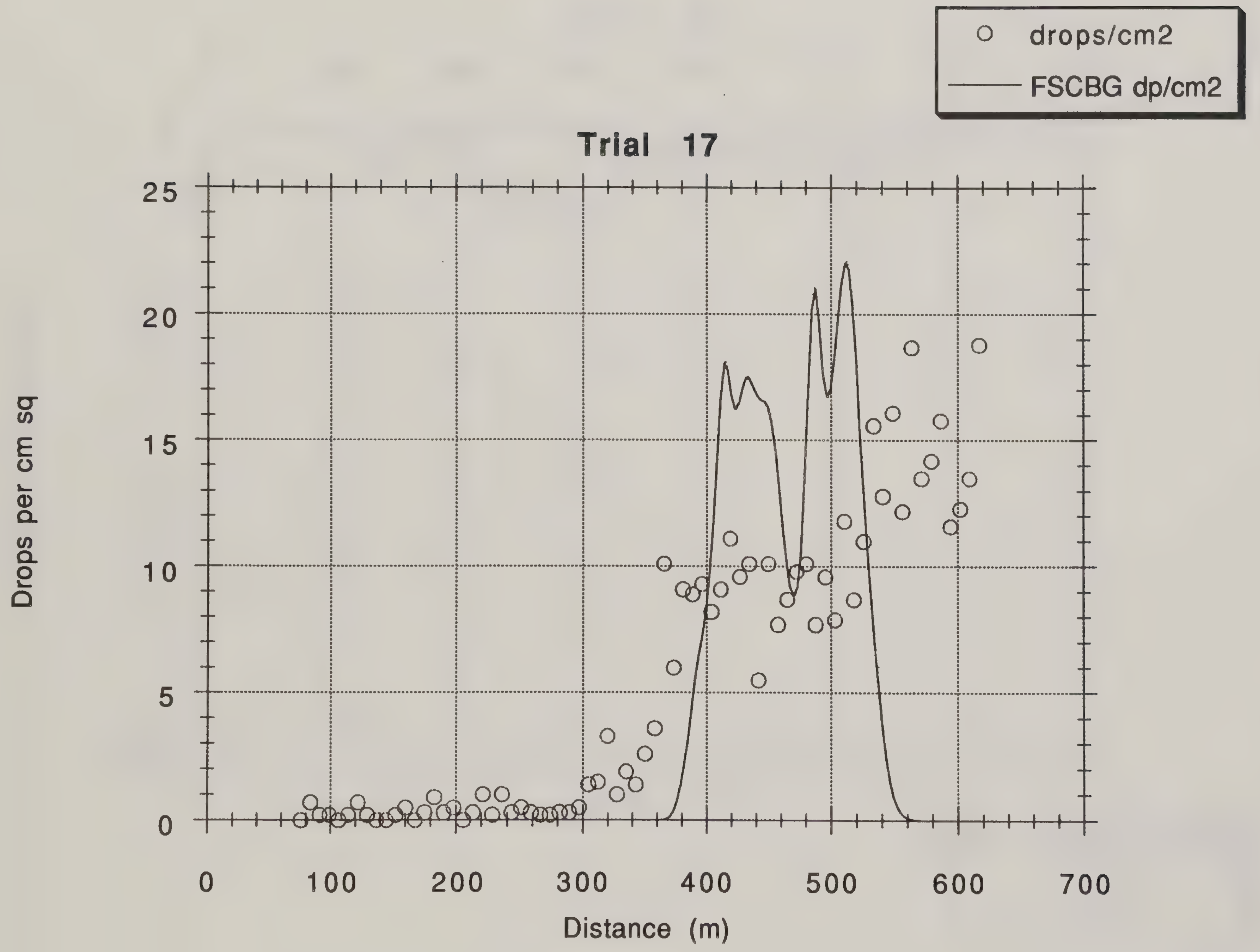
drops/cm2
FSCBG dp/cm2
Trial 15
Drops per cm sq
0
5
10
15
20
25
30
35
0
50
100
150
200
250
300
350
400
Distance (m)



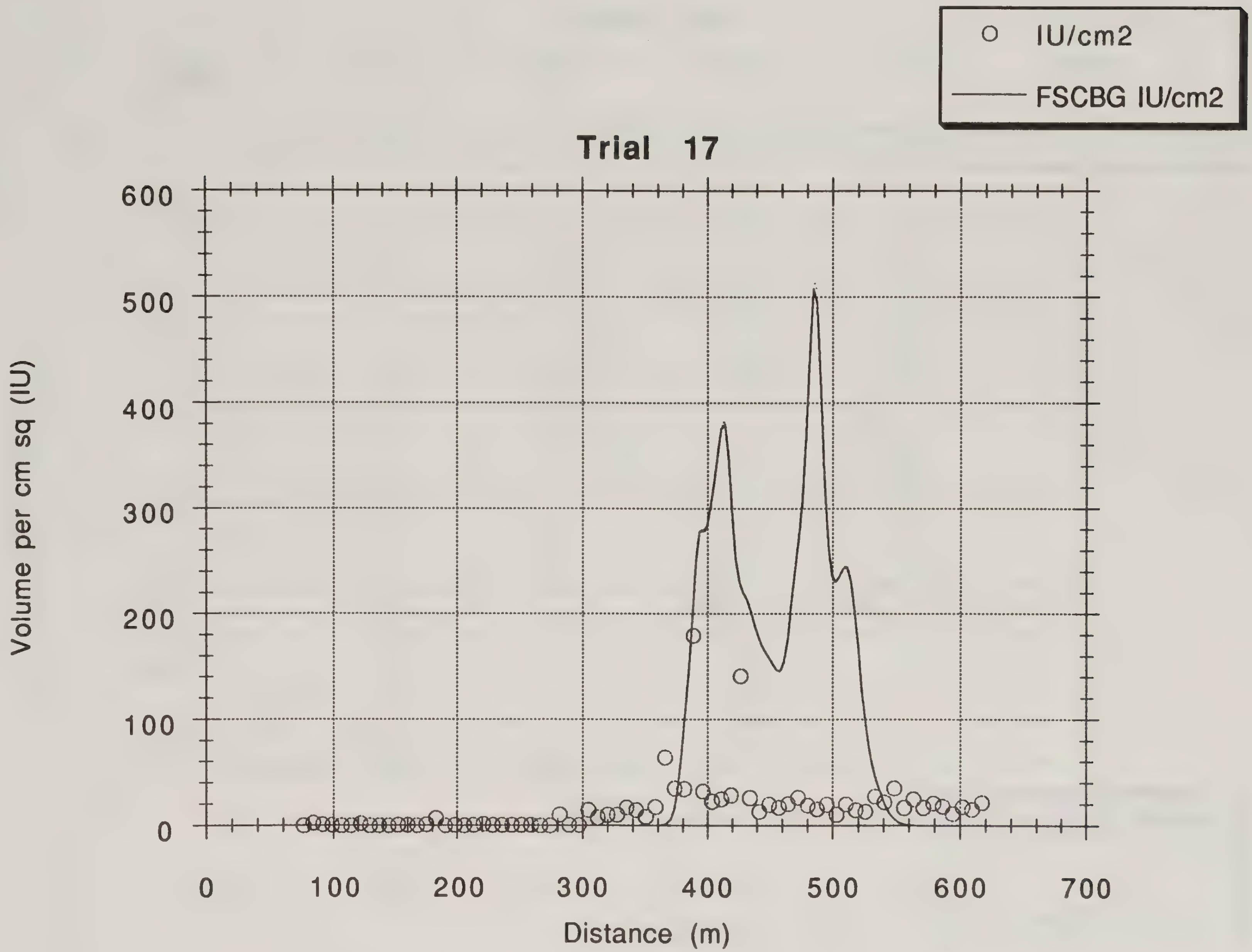
Trial 15
IU/cm2
FSCBG IU/cm2
Volume per cm sq (IU)
500
400
300
200
100
0
0
50
100
150
200
250
300
350
400
Distance (m)

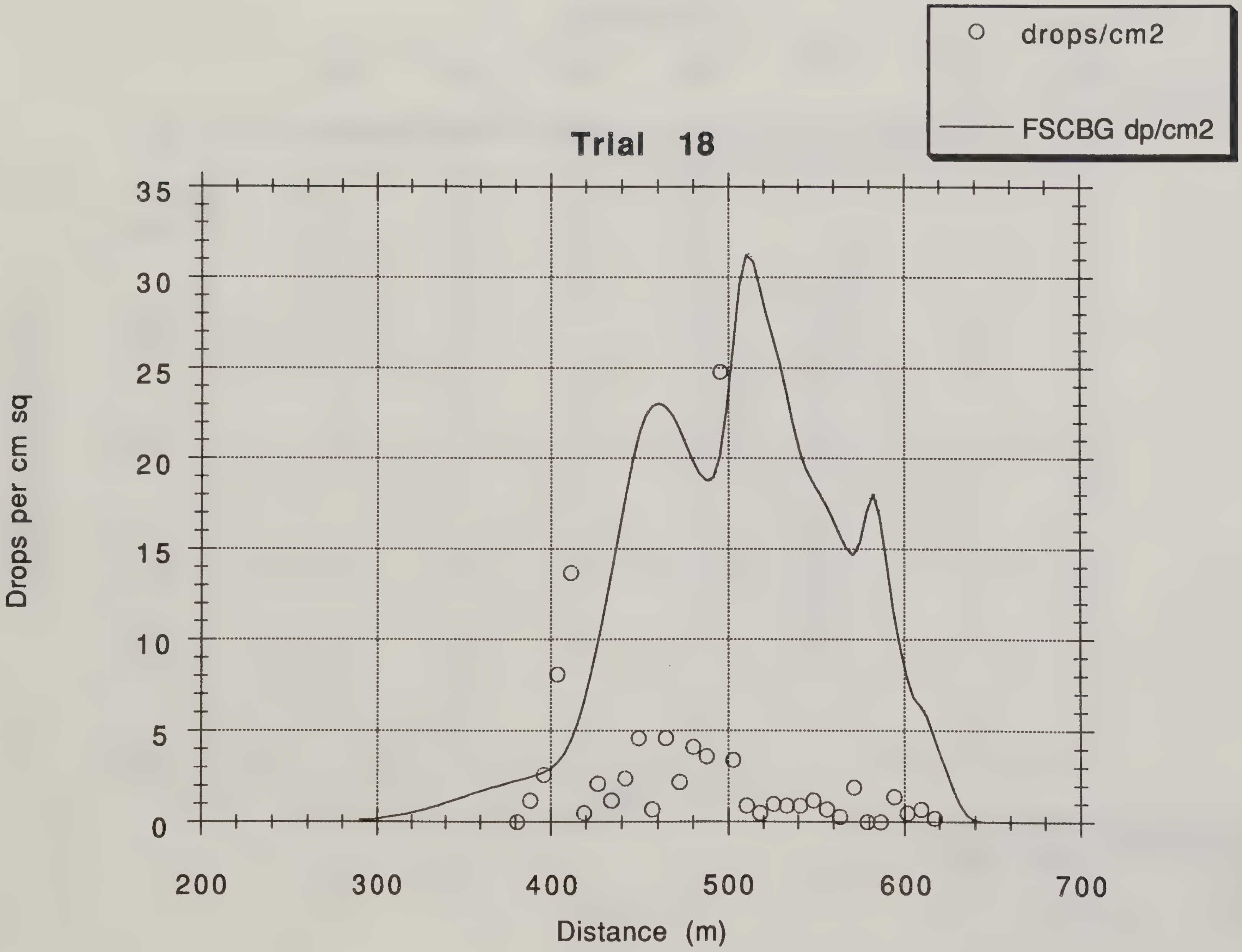

drops/cm2
FSCBG dp/cm2
Trial 16
120
100
80
60
40
20
0
Drops per cm sq
0
100
200
300
400
500
600
700
Distance (m)


Trial 16
IU/cm2
FSCBG IU/cm2
Volume per cm sq (IU)
0
500
1000
1500
0
100
200
300
400
500
600
700
Distance (m)

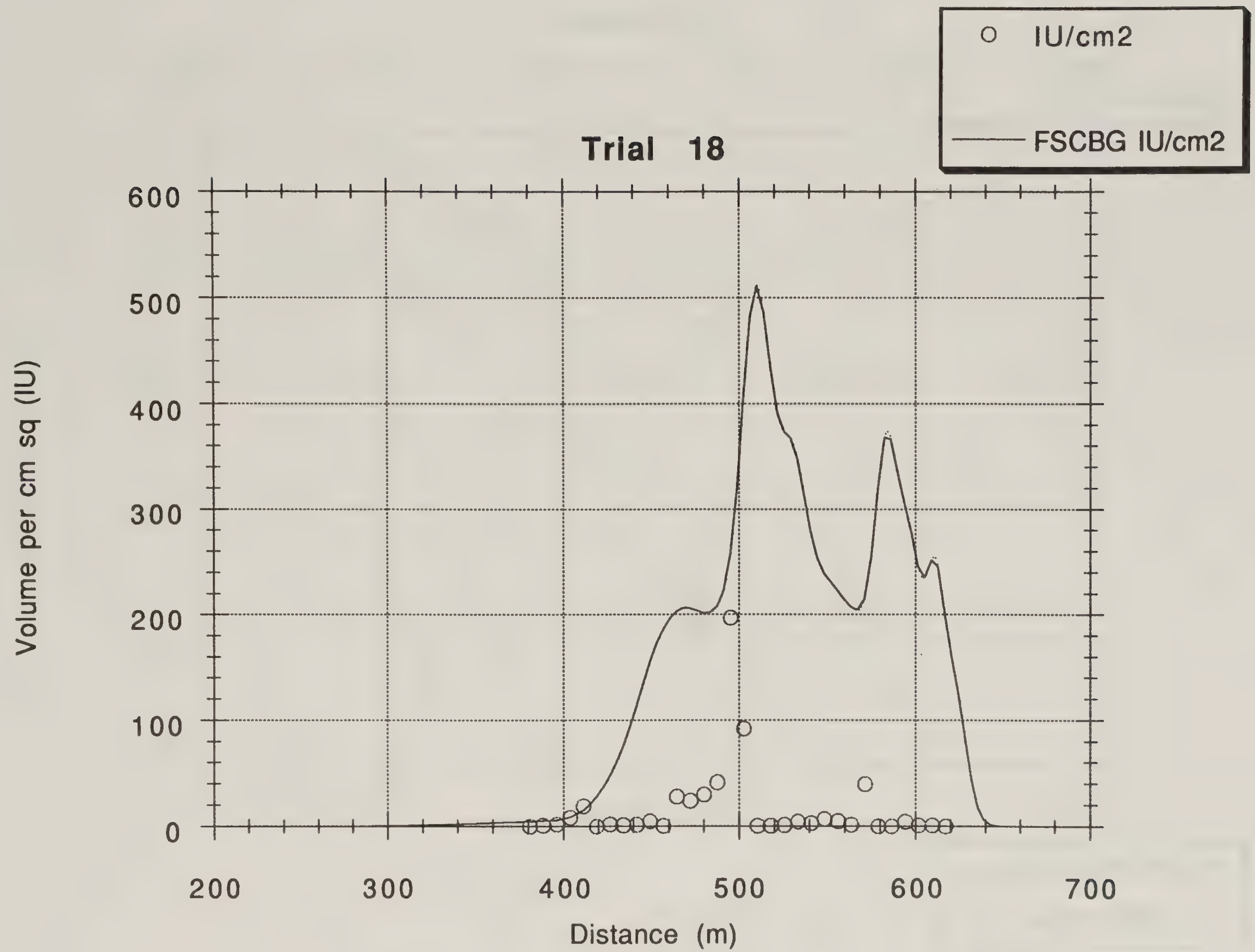


Trial 17
drops/cm2
FSCBG dp/cm2
Drops per cm sq
Distance (m)
0
5
10
15
20
25
0
100
200
300
400
500
600
700

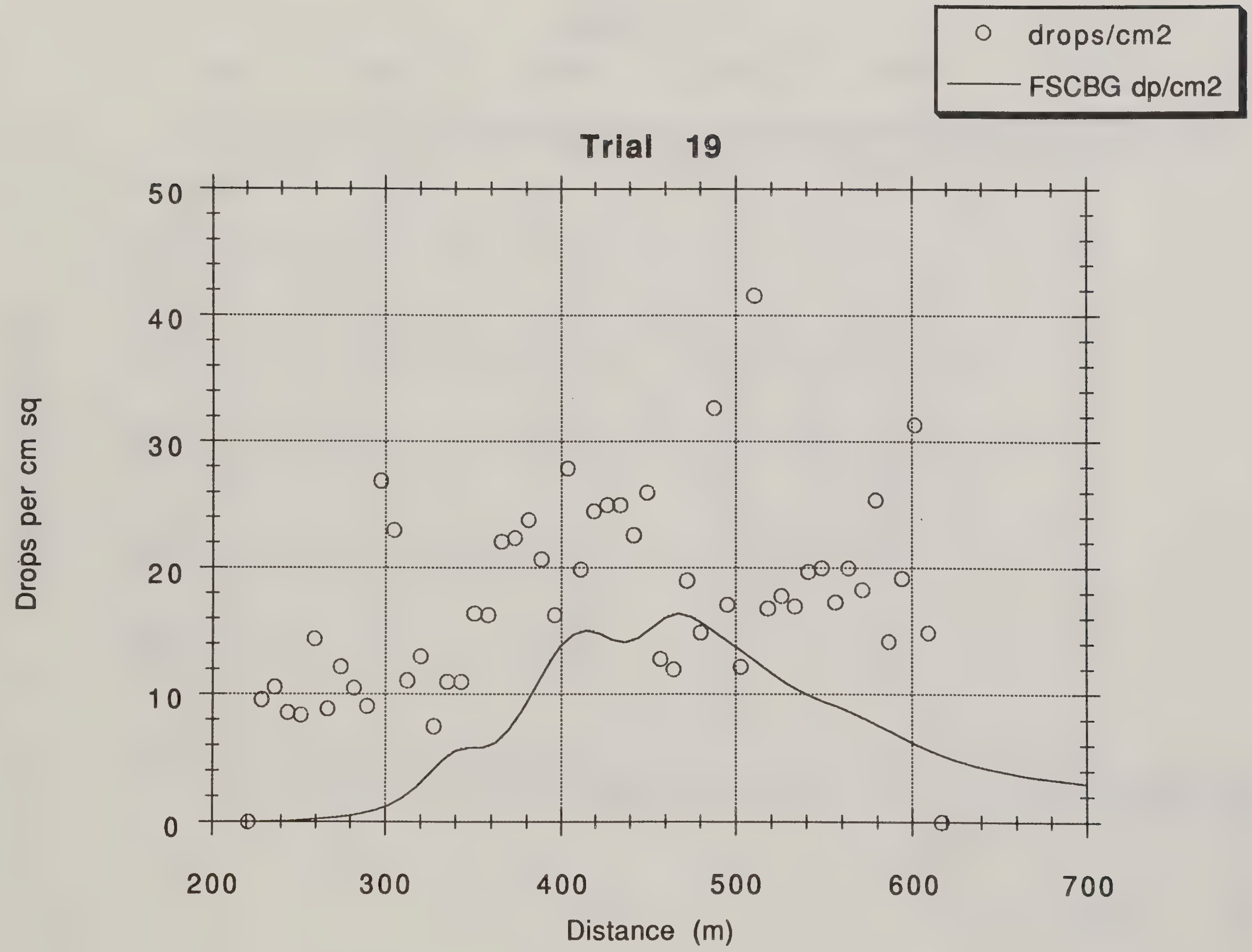

IU/cm2
FSCBG IU/cm2
Trial 17
600
500
400
300
200
100
0
Volume per cm sq (IU)
0
100
200
300
400
500
600
700
Distance (m)



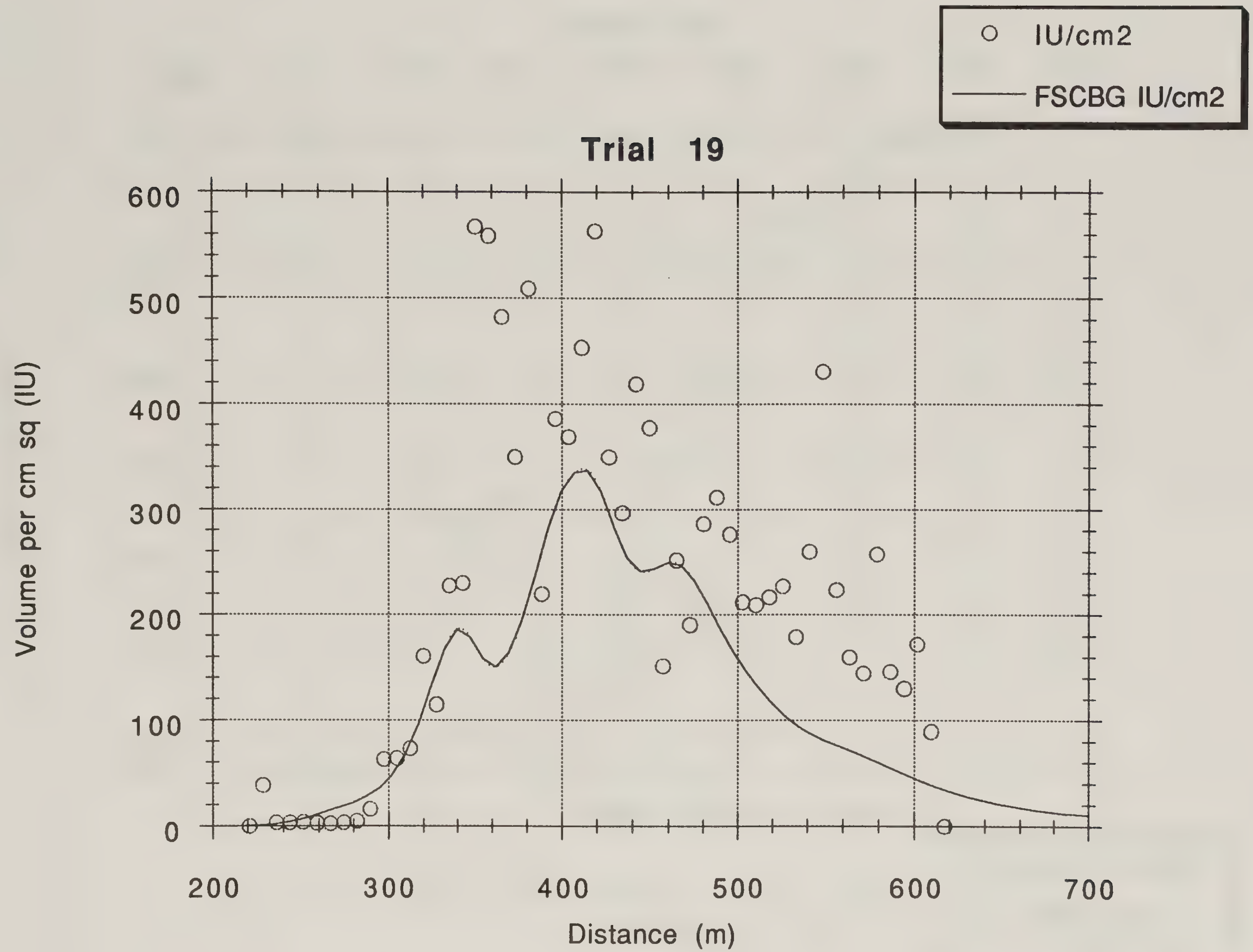
Trial 18
drops/cm2
FSCBG dp/cm2
Drops per cm sq
35
30
25
20
15
10
5
0
200
300
400
500
600
700
Distance (m)

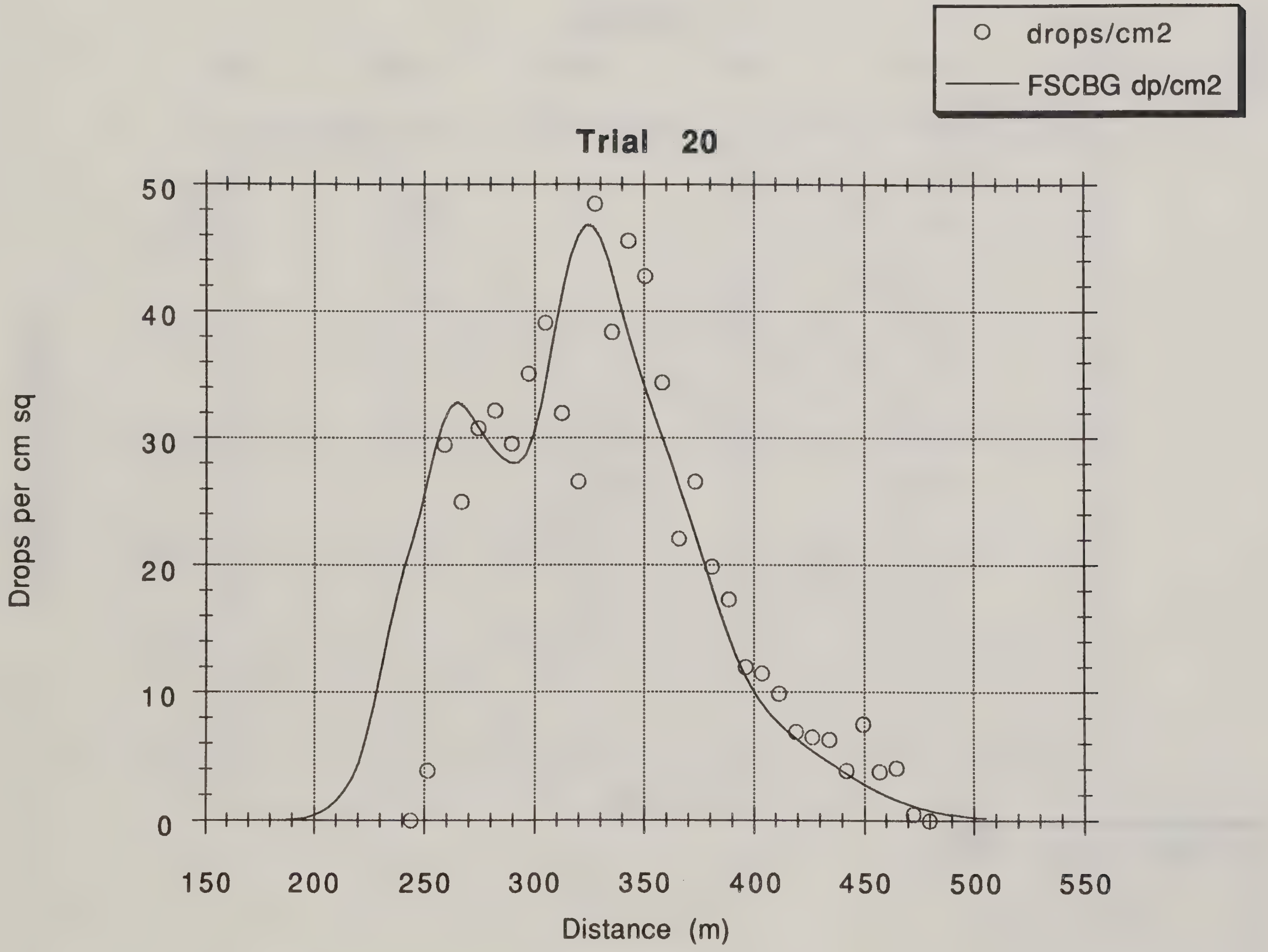


Trial 18
IU/cm2
FSCBG IU/cm2
Volume per cm sq (IU)
600
500
400
300
200
100
0
200
300
400
500
600
700
Distance (m)

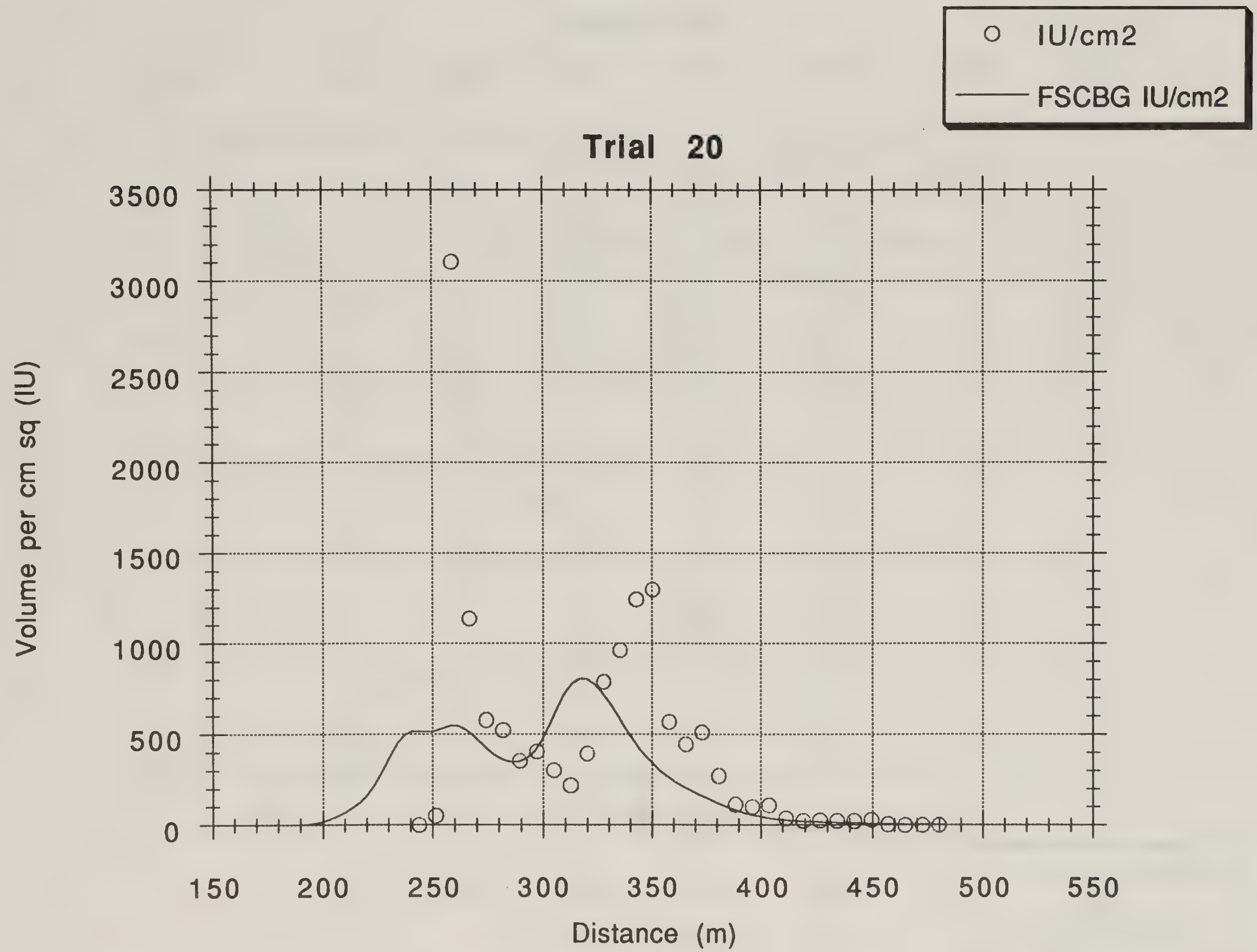


drops/cm2
FSCBG dp/cm2
Trial 19
50
40
30
20
10
0
Drops per cm sq
200
300
400
500
600
700
Distance (m)

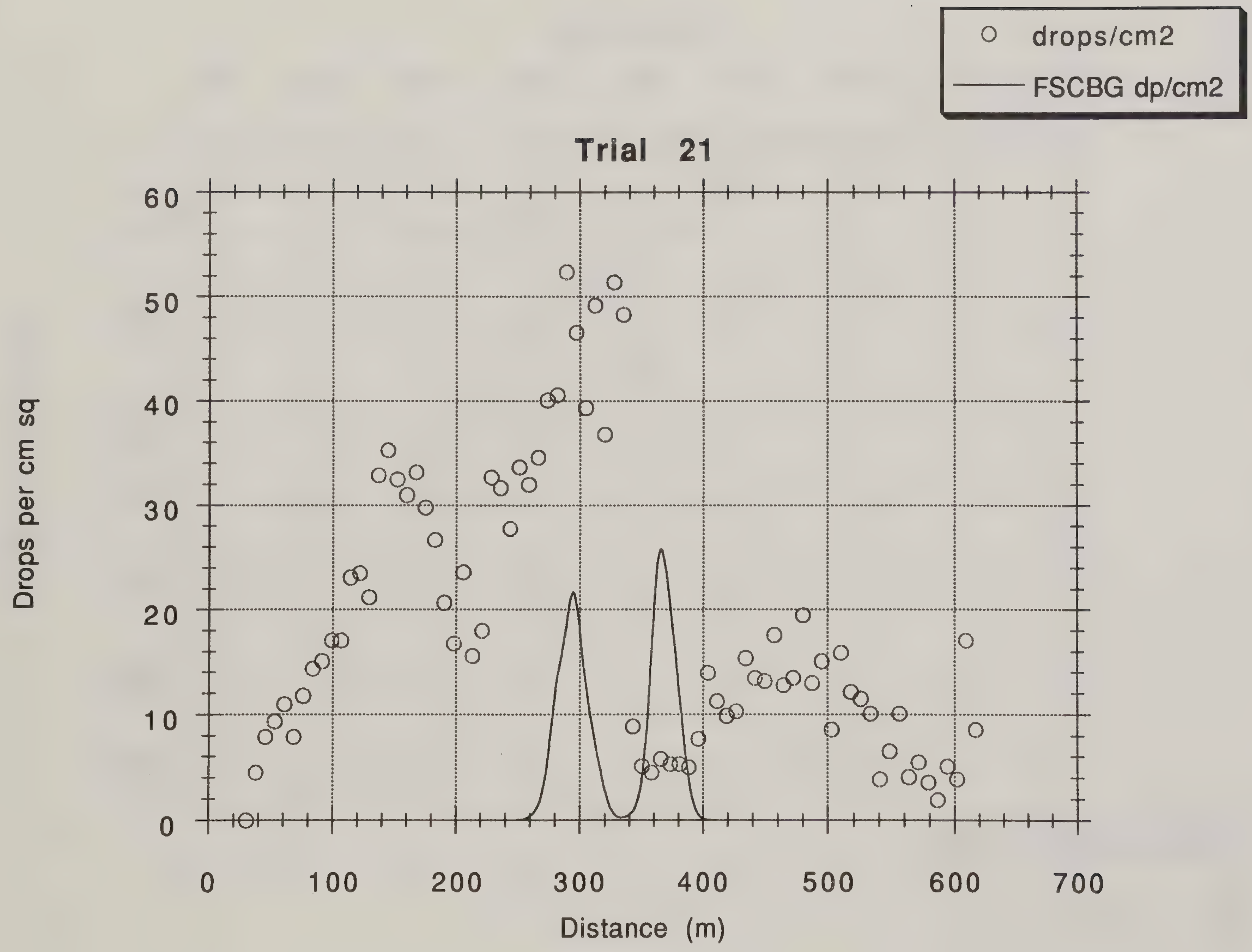

IU/cm2
FSCBG IU/cm2
Trial 19
Volume per cm sq (IU)
0
100
200
300
400
500
600
200
300
400
500
600
700
Distance (m)



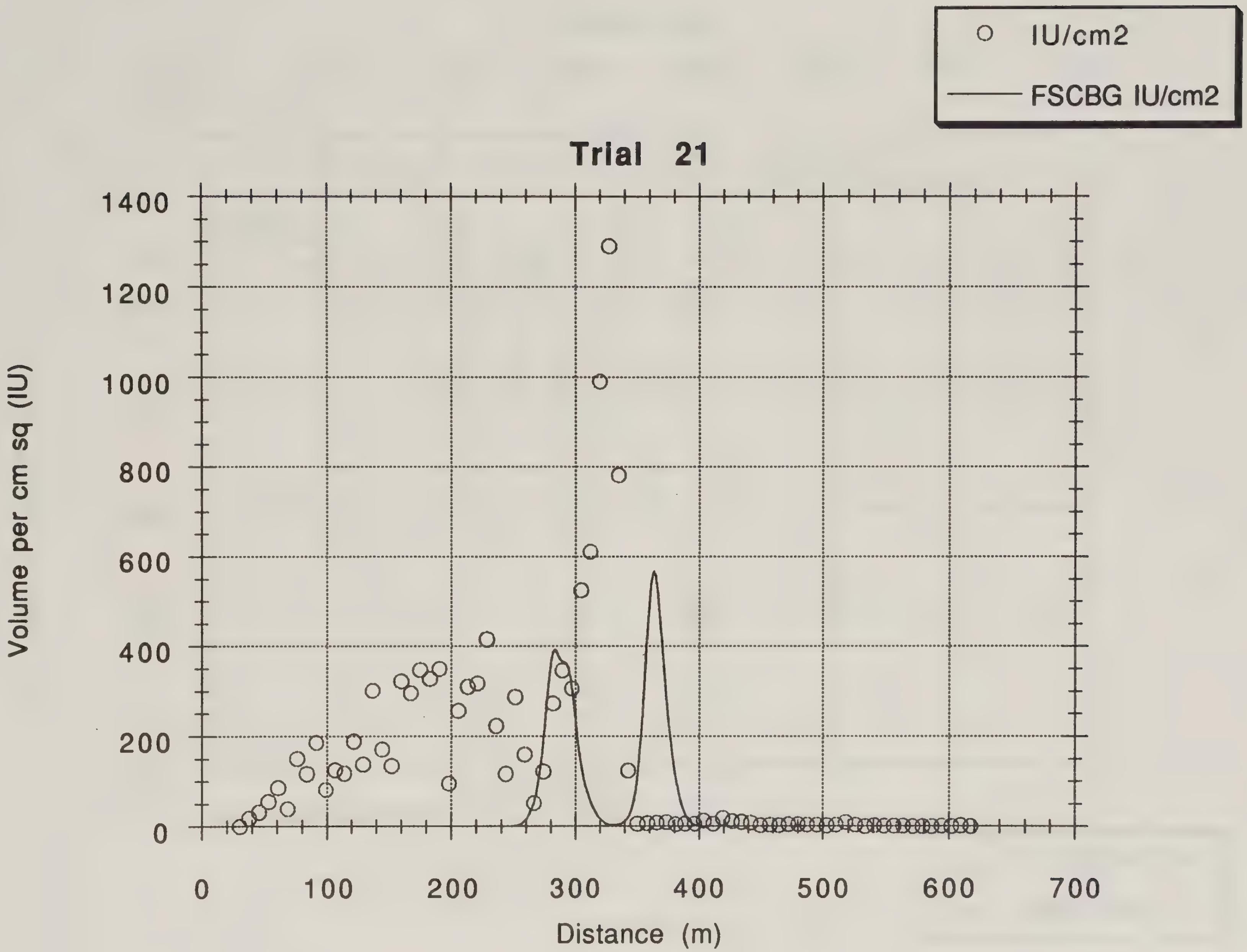
Trial 20
drops/cm2
FSCBG dp/cm2
Drops per cm sq
Distance (m)
0
10
20
30
40
50
150
200
250
300
350
400
450
500
550



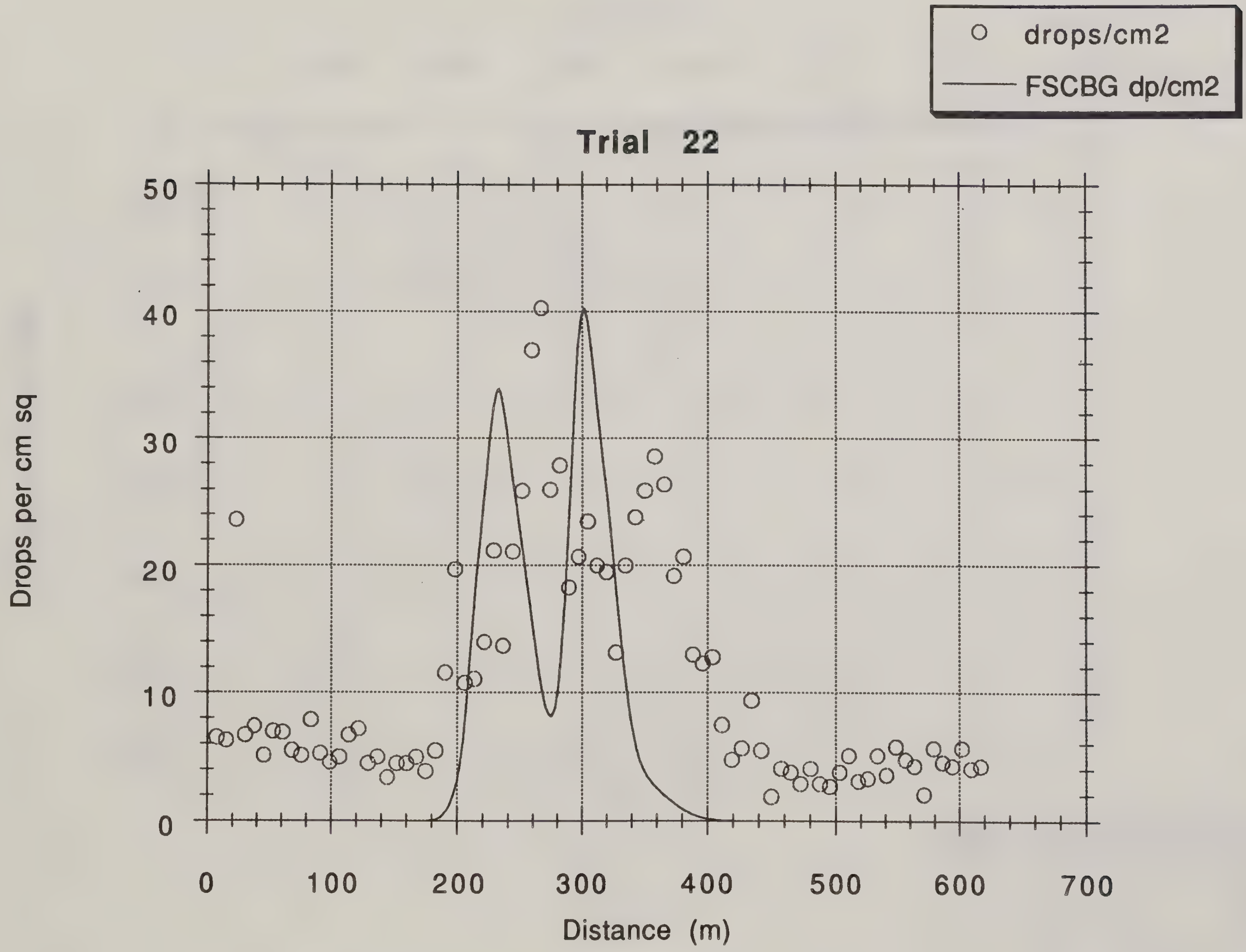
IU/cm2
FSCBG IU/cm2
Trial 20
3500
3000
2500
2000
1500
1000
500
0
Volume per cm sq (IU)
150
200
250
300
350
400
450
500
550
Distance (m)



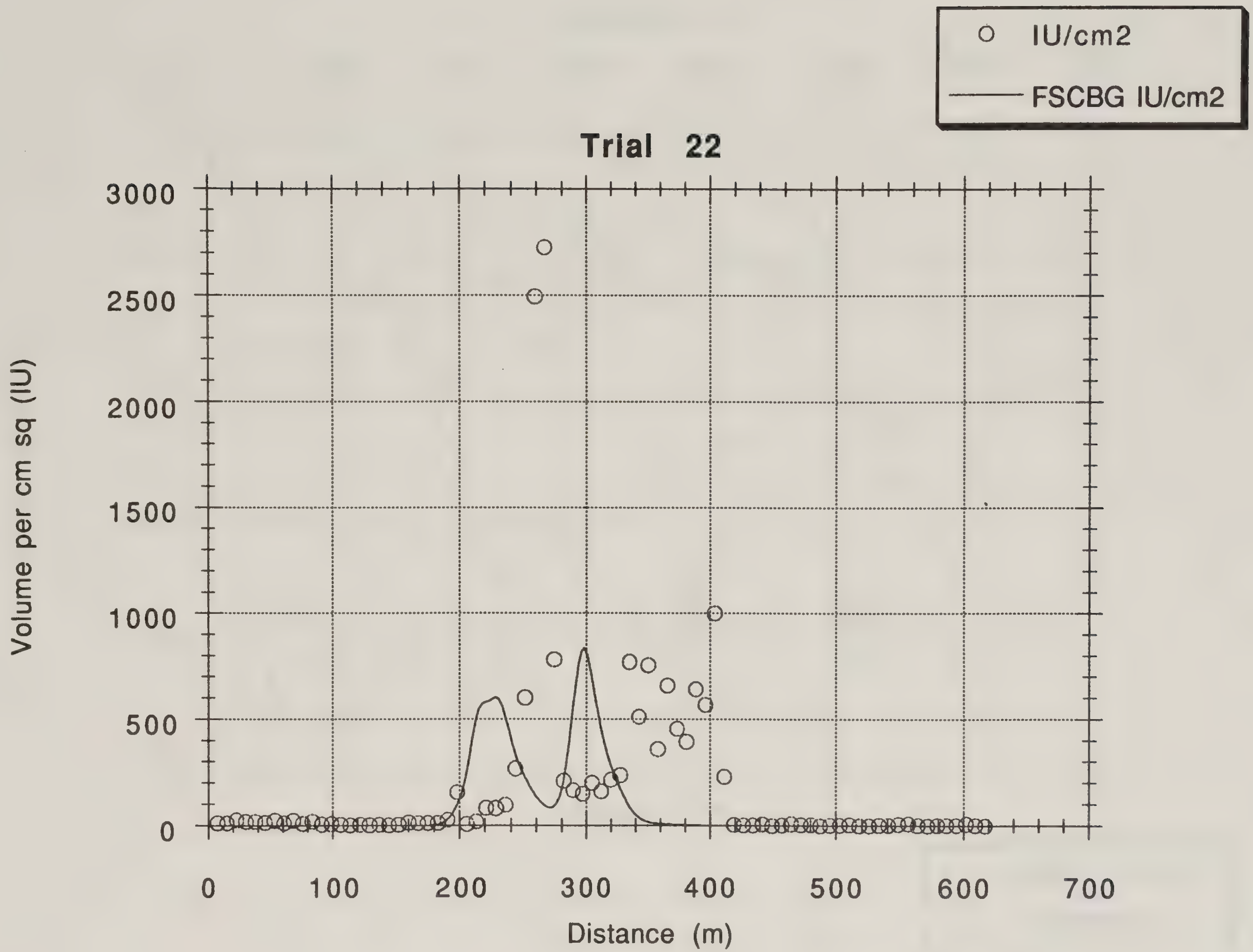
drops/cm2
FSCBG dp/cm2
Trial 21
Drops per cm sq
0
10
20
30
40
50
60
0
100
200
300
400
500
600
700
Distance (m)

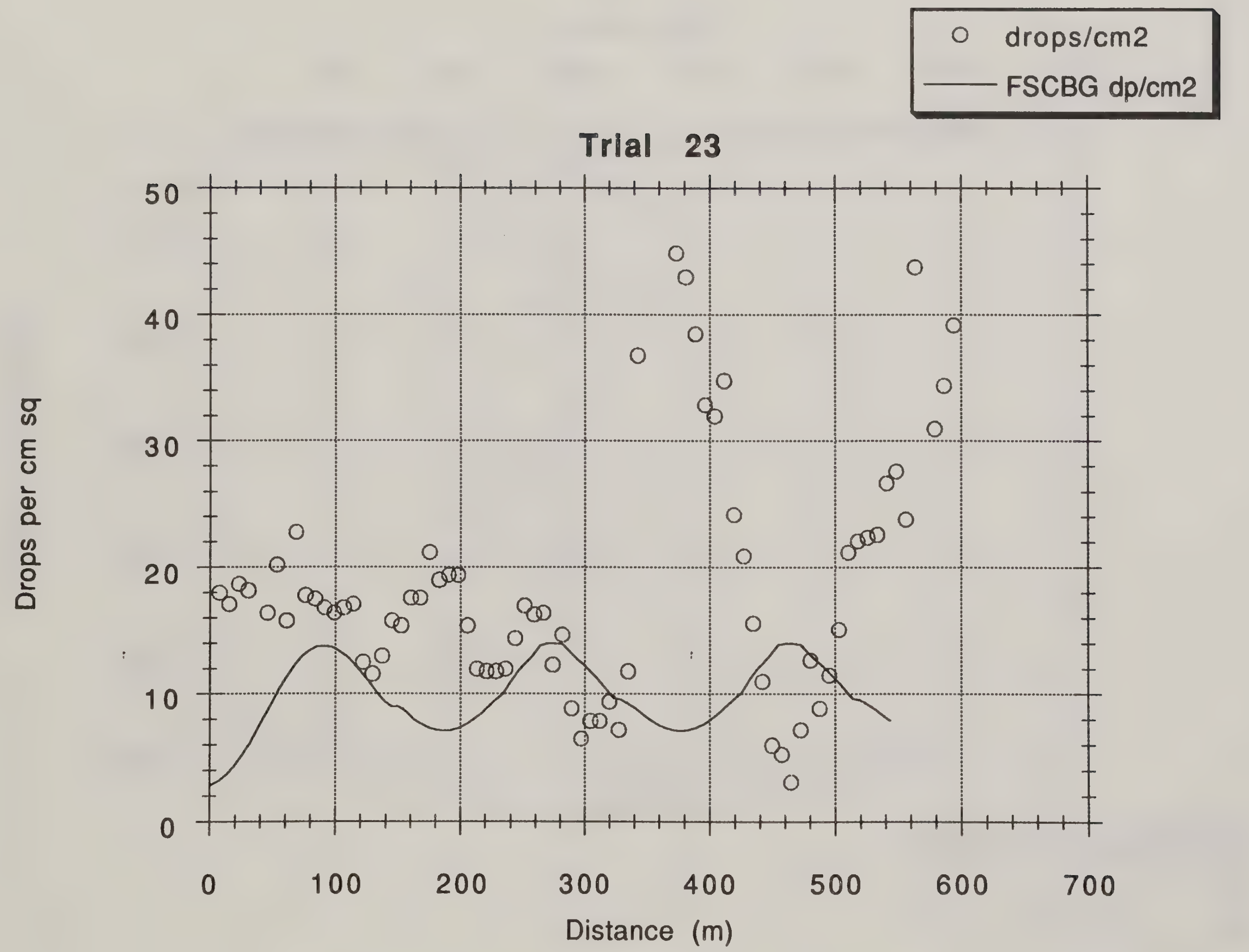


IU/cm2
FSCBG IU/cm2
Trial 21
1400
1200
1000
800
600
400
200
0
Volume per cm sq (IU)
0
100
200
300
400
500
600
700
Distance (m)

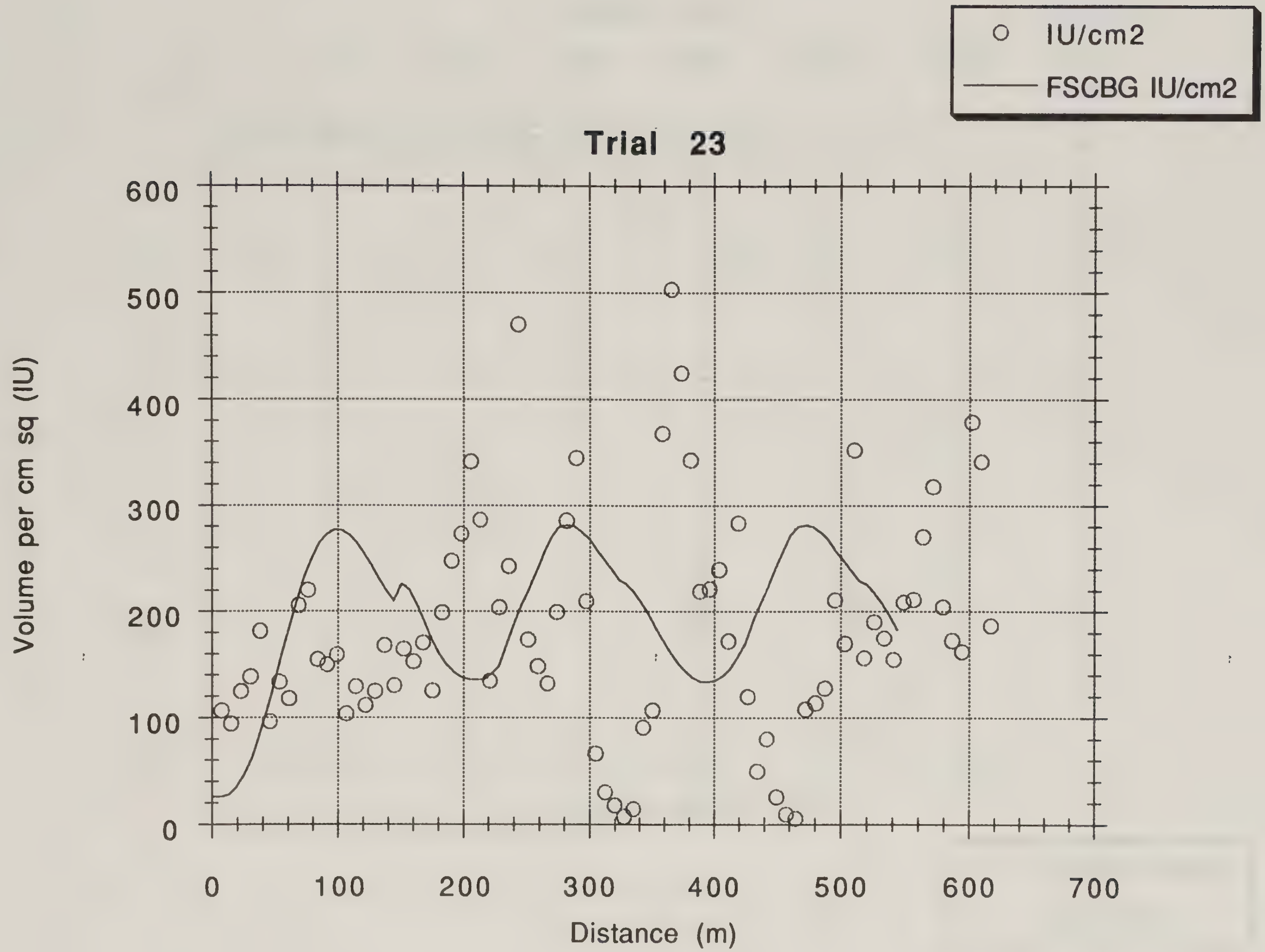


drops/cm2
FSCBG dp/cm2
Trial 22
Drops per cm sq
0
10
20
30
40
50
0
100
200
300
400
500
600
700
Distance (m)

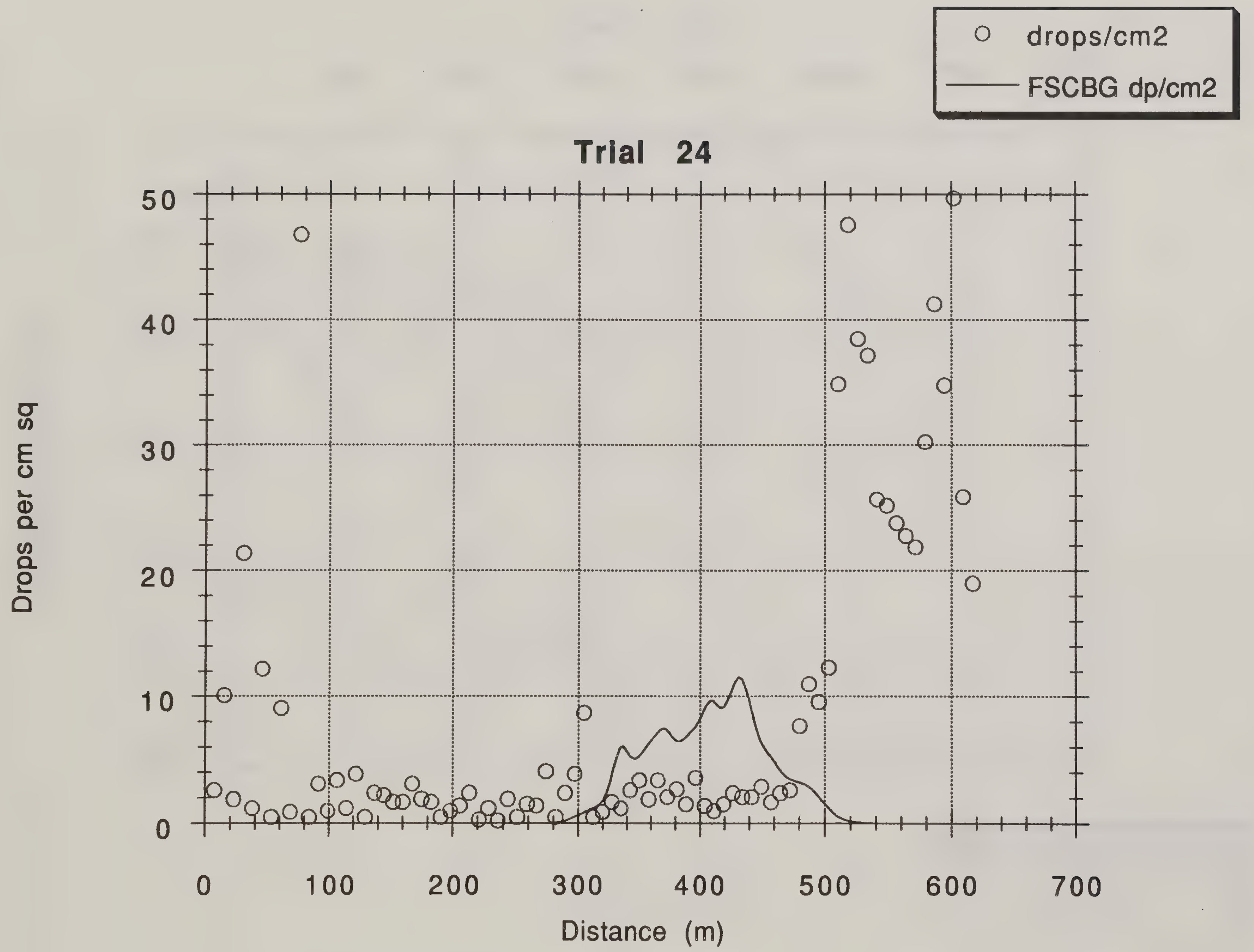

Trial 22
IU/cm2
FSCBG IU/cm2
Volume per cm sq (IU)
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
Distance (m)

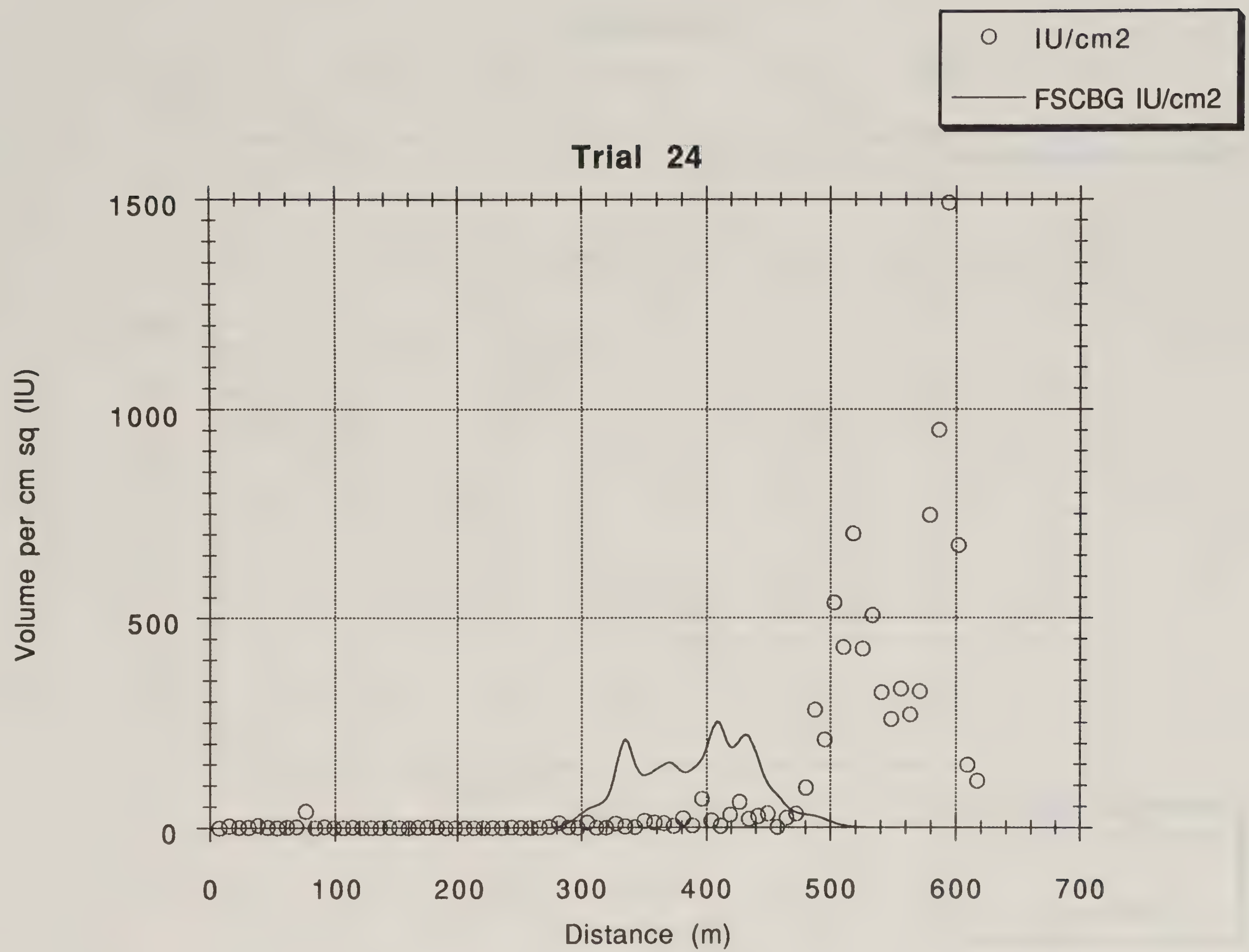


drops/cm2
FSCBG dp/cm2
Trial 23
Drops per cm sq
0
10
20
30
40
50
0
100
200
300
400
500
600
700
Distance (m)

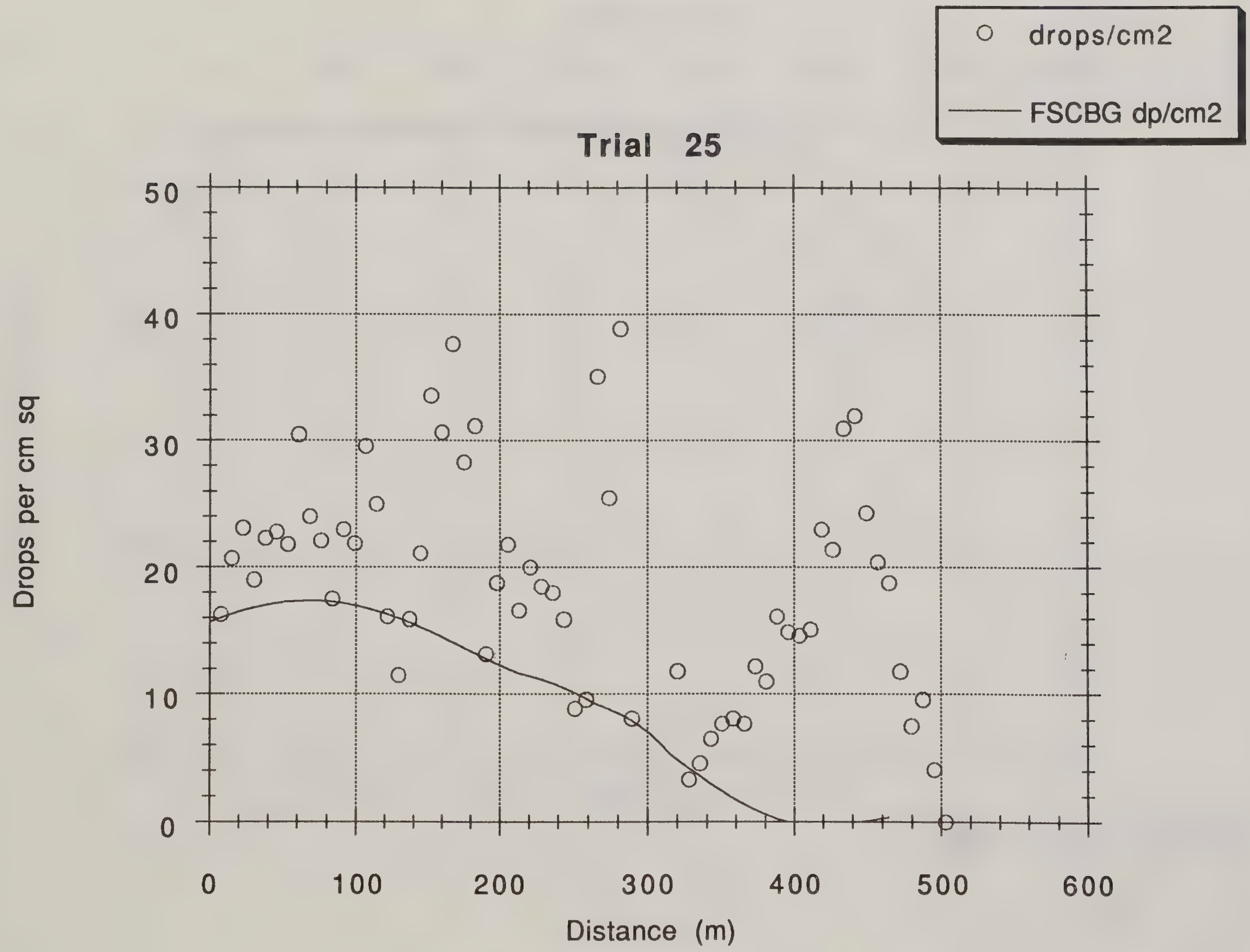


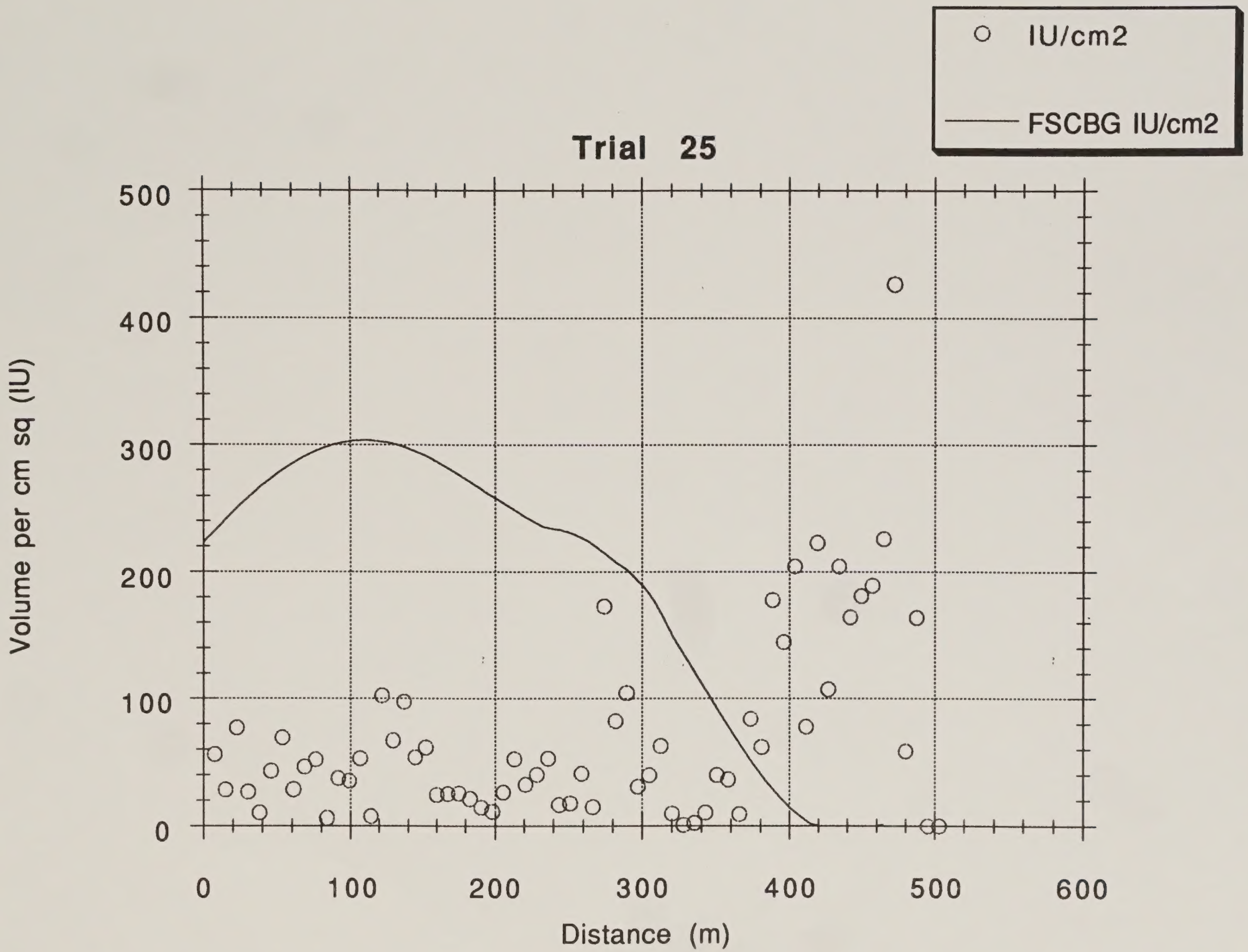
IU/cm2
FSCBG IU/cm2
Trial 23
Volume per cm sq (IU)
0
100
200
300
400
500
600
700
Distance (m)


drops/cm2
FSCBG dp/cm2
Trial 24
50
40
30
20
10
0
Drops per cm sq
0
100
200
300
400
500
600
700
Distance (m)



Trial 24
IU/cm2
FSCBG IU/cm2
Volume per cm sq (IU)
1500
1000
500
0
0
100
200
300
400
500
600
700
Distance (m)


Trial 25
drops/cm2
FSCBG dp/cm2
Drops per cm sq
Distance (m)
0
10
20
30
40
50
0
100
200
300
400
500
600


Trial 25
IU/cm2
FSCBG IU/cm2
Volume per cm sq (IU)
500
400
300
200
100
0
0
100
200
300
400
500
600
Distance (m)